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MULTIPLE PARTICLE PRODUCTION

G. B. Zhdanov

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16. Abstract

New astrophysical discoveries have acquainted us with the world of ultrahigh temperatures and pressures. Under these conditions, particles of atomic nuclei — nucleons — can be accelerated to energies which correspond to heating matter to trillions of degrees. When such particles collide, an unimaginably high energy is concentrated, leading to the simultaneous creation (generation) of a multitude of new particles. This book describes the experimental methods of studying multiple particle generation with the aid of cosmic rays and powerful charged particle accelerators.

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ANNOTATION

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INTRODUCTION

In the World of Ultrahigh Temperatures /3*

As science penetrates to the depths of the Universe, particles of matter with very high temperatures and very large energies are encountered more and more often. Of course the epithets "very high" and "very large" are relative, especially for physics. Our Sun, for example, owes its blinding brightness to the thermal radiation of its outer layers, to a temperature which we may call very low — only 6000° Kelvin. This temperature is "very low" because it corresponds to the average energy of the chaotic motion of the particles of solar matter, an energy which is merely of the order of magnitude of 0.6 electron volts (eV). The whole field of nuclear physics only begins at particle energies measured in many thousands of electron volts.

It was recently learned that the Universe is uniformly filled with radiation, the characteristics of which indicate the existence in the distant past of an ultrahot stage of development. Experiments, as yet not very successful, are being undertaken to measure the temperature of the interior of the Sun by means of detecting the emission of highly penetrating particles, neutrinos. In the laboratory, facilities are being built which reproduce the conditions of the solar interior and which inspire in man the hope of soon controlling thermonuclear sources of energy. Dozens of x-ray stars have already been discovered in our galaxy, and their radiation indicates that oriented streams of particles with energies of many millions of electron volts (MeV) are

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* Numbers in the margin indicate pagination in original foreign text.

circulating in their interiors. This energy corresponds to calculated temperatures of at least tens of billions of degrees (10^{10} degrees).

Other, even more astonishing stars have been discovered — pulsars, which are somewhat like super-large atomic nuclei with densities and pressures characteristic of nuclei and with internal temperatures probably on the order of 10^{12} degrees. Powerful /4
particle accelerators are in operation at Dubna, Serpukhov, Novosibirsk, CERN, near Geneva, Orsay, near Paris, and Batavia, not far from Chicago. Beams of particles, ejected from these accelerators and focused on special targets, create in infinitesimal fractions of a second microscopic but nevertheless ultra-bright "stars", clusters of matter heated to temperatures of a trillion degrees ($\sim 10^{12}$ degrees). These stars are called fireballs by many physicists. Now and then such "stars", which can only be detected by special devices, flare up in our surroundings and even within every one of us as a result of cosmic rays. Although it is still not completely clear what the term "fireball" may or ought to mean, observations allow detailed studies of the radiation emitted by fireballs. Such radiation is not at all similar to light; it is not a portion of the electromagnetic field which has been stripped of its rest mass, but rather heavy quanta of a special type — mesons, field quanta of strong interaction. The energies of these quanta even at the lowest velocities are more than one hundred million times larger than the total energies of photons in the optical spectrum and tens of thousands of times more than photon energy in the x-ray spectrum.

It is not surprising that the laws of emission and the subsequent diverse reincarnations of the heavy quanta, the so-called mesons, are fundamentally distinct from everything known about the light quanta, the photons. One of the most essential distinctions is that many mesons, as a rule, are created simultaneously. At sufficiently high energies, strongly interacting particles can create tens and even hundreds of mesons with each collision, whereas photons are only created one-by-one in collisions of hot atoms and molecules. The reason for this fundamental difference is the intensity (or strength) of the interaction between particles. The strong interaction is about 100 times stronger than in electromagnetic processes.

The strong character of the interaction of particles at high energy leads to still another unusual result. It turns out that in many instances the radiation of heavy quanta proceeds through an intermediate stage of production of various resonances. These are peculiar and unique bits of matter with improbably /5
short periods of existence (on the order of 10^{-23} seconds) and, related to this, with extremely indeterminate values of masses and energies. This is all quite peculiar; it is as if they were a "flickering" world of "not completely created" and indeed in any case extremely unstable creations of nature. The interest in what is occurring in this strange world is not only important to satisfy curiosity concerning the wonders of nature, but also to understand the phenomena which are occurring right now in the "hot shops" of the Universe and which have been occurring throughout the entire Universe since the dawn of its creation.

The Fundamental Forces of Nature

The world surrounding us is in a state of continuous motion and continuous change. It is a world of phenomena and not simply a world of objects, although motion and change are impossible without objects. As with any complete sentence, a predicate cannot exist without a subject (even if it is only understood). So it is with human thought, which has not lost itself in the wilderness of idealism, that motion cannot be imagined without something moving. Therefore it is not surprising that questions concerning the principles of motion, and more exactly, those concerning changes in the state of motion occupy the center of attention of philosophers and physicists.

Two great historic achievements of Newton at the beginning of the 18th century consisted of clearly formulating two laws concerning these very principles. These are, on the one hand, the law of dynamics (the relation between acceleration and force) and, on the other hand, the law of gravitation, the law specifying the force of interaction (attraction) between any two bodies. These laws enabled one to clearly explain, as Newton himself wrote, "all motions of celestial bodies and the sea" (he was referring to the tides). But these very laws cannot describe the majority of phenomena occurring in man's surroundings of the everyday world.

Still another half century was needed so that Coulomb, Faraday, Maxwell and other physicists of the 18th and 19th centuries could discover and study the laws of motion of new forces. These are the electric and magnetic forces, which turn out to be closely related to one another in the single electromagnetic /6 interaction of any electrically charged bodies, and sometimes of bodies that are on the whole neutral. As was later shown, these forces are determined by the scattering of atoms and molecules of all substances and by the aggregate state of any bit of matter.

Nearly another half century passed, and Rutherford discovered forces of a new type, which "support" the entire structure of the exceptionally dense matter of the atomic nucleus, and which subsequently received the name, strong interaction. In contrast to the electrostatic and gravitational forces, the strong interaction turned out to be short-ranged, but, by way of compensation, significantly more intense.

As for the property of the "intensity" of forces, we will have to wait until later for an explanation. For the time being we will merely note that basically owing to the study of the strong interaction and of the phenomena of nature dependent on it, it has been ascertained that the representation of atomic matter as the most simple, qualitatively stable, and indivisible "little building blocks" of the universe has no basis in fact.

However, the discovery of an interaction of still another type, the weak interaction, also made a significant contribution to the perception of the variability of the elementary structural units of matter. Precisely as a consequence of the weakness of this interaction, its characteristic carrier, the neutrino, turned out to be capable of penetrating practically everything and is almost imperceptible. It was "captured" for the first time merely some 15 years ago by F. Reines and C. Cowan with the aid of a nuclear reactor, a powerful source of neutrinos.

The weak interaction is really extremely weak. It is about 10^{10} (10 billion) times weaker than the electromagnetic interaction and about 10^{12} (trillion) times weaker than the strong. But the most interesting thing is that even the weak interaction (at least according to current conceptions) is much stronger and hence much more important for the understanding of the stability and structure of elementary particles than gravitational interaction, which was discovered long ago. The peculiarity of this situation lies in the fact that although gravitation is "popular" and universal, acting between any material bodies, and being by far the longest-range force, it does not manifest itself at all in the world of elementary particles. Futhermore, because of the weakness of gravitation, its carrier (gravitational waves) /7
has been, in a simple sense, detected, but indeed not very convincingly, only in the last few years by means of exceptionally sensitive devices.

Each of the four fundamental forces of nature (strong, electromagnetic, weak, and gravitational) has its own typical "carrier" in the form of discrete "bits", the quanta. For the strong interaction such quanta are pi-mesons or simply pions; for the electromagnetic they are photons (quanta of light); for the weak they are neutrinos; and for the gravitational they are gravitons (the graviton, however, is at present not a particle which is available to the experimenter).

In addition to these four particles, many tens of others have been discovered and examined by physicists. As a rule, each particle can participate in two or more types of interactions. For example, the electron, positron, and the muon, which is much heavier but otherwise quite similar to the electron and positron, can participate in both the weak and electromagnetic interactions. Together with the neutrino and anti-neutrino, these particles make up the family of leptons.

The neutron barely responds to the electromagnetic force, but it is, however, very active in the case of strong interaction. The proton and the pi-meson participate in the weak, electromagnetic, and strong interactions. All strongly interacting particles constitute the family of hadrons.

By means of the strong interaction, as already mentioned, atomic nuclei are "cemented" together. They constitute the basis of all the matter of the Universe and are multiple combinations of only two of the most simple "little building blocks", the proton and the neutron. On this interaction depend the most "emphemeral" and short-lived objects of the microworld, which are as diverse as the nuclei. These are the resonances, which decay spontaneously in 10^{-23} seconds! Many times more long-lived than the resonances are the particles which disintegrate as a result of the weak interaction. An extreme example is the neutron, which in a free state "lives" for about 15 minutes on the average. In this manner a difference in the intensity of the interactions is reflected in the time scale, in the time necessary for the transformation of a particle. ...

Birth, Death and Conservation — Three Facets of the Animate and Inanimate Worlds /8

In every specific case of interaction between material bodies, two mutually complementary components can be clearly distinguished. The first is the souce of the strength of interaction, which can be characterized quantitatively by the magnitude of the corresponding charge. To the extent that the interactions are different, the concept of charge can be generalized to distinguish between hadron, lepton, and gravitational charge. In the last case one is talking in fact about the mass of the body, and it is necessary to recall that in physics two different concepts of mass are clearly distinguished: "inertial" mass (a measure of inertia) and "heavy" mass (gravitational). The proportionality of these masses (which is transformed to numerical equality with a suitable choice of units of measurement) is graphically manifested in the conditions of weightlessness within space ships, and this in itself is an important law of nature since it is not true a priori.

An important characteristic of any charge is first, its conservation in interaction processes (more precisely, the conservation of the total charge of all the particles taking part in the interaction), and second, the discrete (quantum) character of its value, i.e., the ability to take on only those values (negative included), which by convention are confined to whole numbers. The different signs associated with magnitudes of the charges are related to the existence of anti-particles: the electric charge of the proton is +1, and that of the anti-proton, -1; the charge of the electron, on the other hand, is -1 in contrast to that of its anti-particle, the positron. In the case of the neutrino and anti-neutrino, the electrical charges are equal to zero, but they differ with respect to lepton (weak) charge and spin orientations (their particular angular momenta).

The second component, which is no more abstract than the
first, was given the name, "field" by physicists. In the case
of static interactions (e.g., electrostatic or gravitational)
the concept of field simply involves the definite region in which
the force acts. This is characterized quantitatively by the mag-
nitude of the force on a unit test charge. However, the more
general case is the variable (in time) field, which by convention /9
can be represented as a combination of waves, or particles. It
has become clear, thanks to the successes of quantum physics,
that waves and particles are two sides of the same coin. (That
is why there is a comma before the word "or" in the previous
sentence.) These wave particles, or in other words, quanta of
radiation, are also the transmitters of the interaction of their
sources (charges). But in principle, they can preserve their
independence for an arbitrarily long time, irrespective of their
origins. Perhaps the clearest illustration of this statement is
the recently discovered (in 1965) remnants of cosmic radio-fre-
quency emission, our inheritance from the hot stage of develop-
ment of the Universe. During the last billion years it has been
cooling off, but it has retained its characteristic feature —
its spectral distribution described by Planck's Law.

The process of interaction includes the emission of quanta of radiation by one source of the strong field, and absorption by another source. It is significant that with this both sources, in general, undergo changes. Only in the static case (as in the case of a planet moving about the Sun or electrons about an atomic nucleus) do they remain unchanged, if one ignores the change in spatial position, the type of "recoil" with the "shots" of field quanta. The change of state of each source is limited by the specific conservation laws. But the state of the interacting system on the whole is subjected to an even stricter law. For example, the proton and neutron can exchange electrically charged pions, but while the charges of the individual particles change, the charge of the system as a whole remains equal to +1 (in units of electron charge). The field itself can also be one of the "partners" in the interaction, as, for example, in the absorption of high energy photons in the strong electric field of the atomic nucleus. The photon vanishes, being converted into a pair of particles — an electron and a positron.

One and the same particle can act at one time as the source of radiation, and another — as the quantum of radiation. Thus, the charged pion is the source of electromagnetic radiation and the field quantum of the strong interaction.

The atomic theory of the structure of matter of the ancients /10
has undergone a substantial change. Instead of the combination of identical, immutable, and indivisible atoms, various transformations occur in the world of the smallest elementary particles, especially at high energies, in which some particles disappear and others "come into the world". The property of particle symmetry, which is manifested in the laws of conservation of the various charges, replaces the notion of immutability. This situation is reminiscent of the evolution of the form of matter with the continuous death of some organisms, the birth of others, and the conservation of the "program of life", the inheritance of information directed by the complex combination of metabolic reactions.

The Puzzle of Secondary Cosmic Radiation in Multiple Meson Generation

The bold hypothesis that the carrier of the short-range interaction between the constitutents of the atomic nucleus, the nucleons, must be some distinct, massive quantum was expressed for the first time by H. Yukawa as early as 1935. Several years later charge particles with a mass intermediate to the electron and proton (and therefore called mesotrons or mesons) were actually discovered by C. Anderson and S. Neddermeyer in cosmic rays. This serves as a splendid example of the ability to discover the laws of nature by means of theoretical physics.

In reality, however, it did not turn out to be that simple. True, it was well known that cosmic rays were streams of primarily charged particles of enormous energy and penetrating power. At the same time many strange things were occurring. It turned out that the primary particles, i.e. those arriving directly from cosmic space, were protons; those observed in the depths of the atmosphere were mostly electrons; and those remaining after passing through large thicknesses of matter (through the upper layers of the Earth) were for some reason those very particles called mesons. But if mesons penetrate matter so well, then it /12 is not understood why they are so poorly absorbed by atomic nuclei; indeed, nuclear particles are nucleons and are sources of mesons, the carriers of the strong interaction. In any case it turned out that the generation of mesons by protons occurs with a much larger probability than the inverse process, their absorption.

Besides this, the appearance of electrons can be attributed to the direct effect of primary protons only with great difficulty. True, the process of the production of pairs of particles, the electron and positron by one photon, had already been observed.

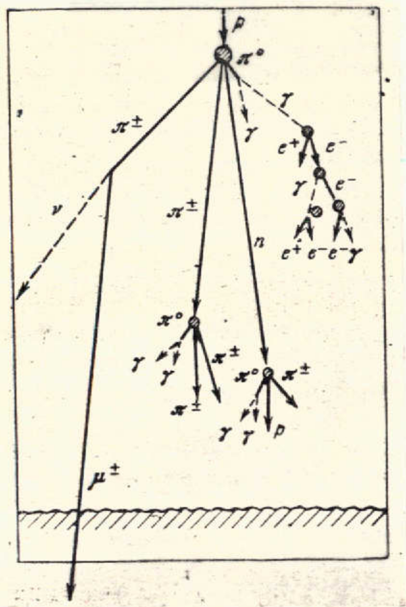

Figure 1. A photograph of an electron-nuclear shower in a Wilson cloud chamber (S.Chao). The primary particle (indicated by the arrow) produces, in the 5th plate from the top, two penetrating particles (the second was caused by nuclear spallation in the 7th plate) and two electron cascades in the lower-right part of the chamber.

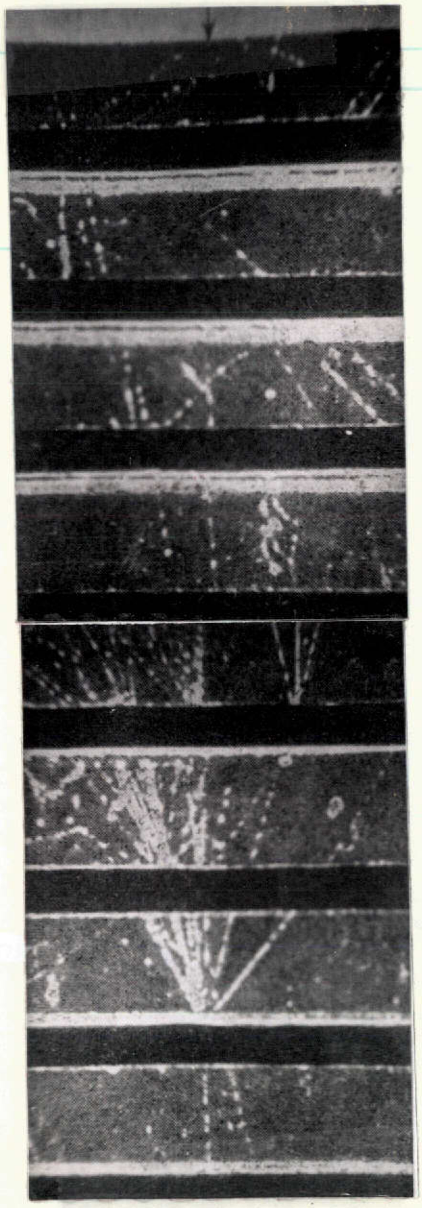

Figure 2. The formation of secondary cosmic radiation in the process of multiple production of charged ($\pi^{\pm}$) and neutral (π^{o}) pions. The nucleons (p, n) together with the non-decaying mesons ($\pi^{\pm}$) form the nuclear active component, the decaying $\pi^{\pm}$ mesons form the penetrating component ($\mu^{\pm}$, ν), and the decaying π^{o}-mesons form the electron-photon ($e^{\pm}$, γ) component of the secondary radiation

But the emission of a photon by a particle as massive as the proton is certainly a rare process.

The resolution of all these difficulties required decades of intensive work by physicists of many countries, including Soviet scientists who carried out experiments in the high-altitude regions of the Pamirs and in airplane flights in the stratosphere. Experiments using the Wilson cloud chamber, from which were obtained photographs like the one shown in Figure 1, came closest of all to resolving these difficulties.

In the Wilson cloud chamber there were 8 lead plates, each of a thickness of about 13 mm. Any penetrating particle (be it a proton or a meson) passed through four plates of the chamber and only in the fifth from the top did it create a cone-shaped diverging bundle of particles. The particle of the extreme left of this bunch turned out to be another penetrating particle (evidently a meson), but the basic part of the cone was formed by two bunches with a gradually increasing number of particles in each bunch. The experimental eye of the experimenter confirmed that both bunches of newly generated particles were made up of electrons.

All complex phenomena of a similar type were called electron-nuclear showers in contrast to the simpler cascade showers in which only electrons take part. It was conjectured that in all these cases the electrons are not generated directly, but that some type of intermediate, extremely short-lived particle first appears. The situation did not progress any further until physicists learned to obtain protons of high energy from accelerators. Then it became clear that such a particle, which decays into two photons in an infinitesimally short time, actually exists in nature. This particle was called the pi-zero meson (π^{0}).

Meanwhile, new, extremely important information again emerged /13 from cosmic rays. In 1947 S.F. Powell (England) and co-workers discovered — in the course of lengthy experiments with nuclear photoemulsions — a completely new phenomenon. In all cases there was seen on the photographs a relatively "bold" track growing even thicker towards its end and joining at its beginning a thinner track of another charged particle. This track, in its turn growing thicker, joins at the beginning an extremely thin and broken track of a third particle. Careful study of the characteristics of all three tracks showed that the photoemulsion registered a two-step decay process of the type

$$\pi \rightarrow \mu \rightarrow e.$$

In this process, the π particle, called a pi-meson (or pion) by the authors, is typically 1.3 times heavier than the μ particle (muon), and more than 200 times heavier than the electron. This pion coincided with the particles discovered by Anderson and Neddermeyer. In addition, the pion turned out to be very close in mass to the short-lived particle which decays according to the scheme $\pi^0 \rightarrow 2\gamma$ discovered later in accerator experiments. The π^0 particle, as was soon established, is a neutral variety of pi-meson.

In this way all the fundamental processes were worked out by which primary cosmic radiation is transformed to secondary radiation. The general scheme of this transformation process is represented in Figure 2. As a result of a collision of a high-energy proton with the nucleus of any atom in the air, several charged (π^+, π^-) and neutral (π^0) pions are produced by means of the strong interaction. The completely analogous process of the generation of several new π^+, π^- and π^0 mesons on nuclei can be extended even further. As a consequence of this, both protons and $\pi^{\pm}$ mesons can be placed in the category of nuclear-active particles.

In addition to this, the charged pions, decaying into muons as a result of the weak interaction, can act as the origin of the penetrating component of cosmic rays. The π^0 mesons, however, initiate the chain-like processes

$\pi^0 \rightarrow 2\gamma$ (spontaneous decay), (1)

$\gamma \rightarrow e^+ + e^-$ (creation of a pair of particles by the photon), (2)

$e^{\pm} \rightarrow e^{\pm} + \gamma$ (radiation of electromagnetic quanta). (3)

The subsequent repetition of steps (2) and (3) gives rise to the /14 electron component of the secondary radiation, which develops by means of the electromagnetic interaction. Thus, the solution of the problem of secondary cosmic radiation (the active creation of passive particles) led to the discovery of the completely new and unique process of multiple generation of decaying particles (mesons) as a result of collisions of primary, strongly interacting particles of sufficiently high energy. The threshold of "sufficiently high energy" corresponds to cosmic ray energies of 1-3 billion electron volts (GeV, an abbreviation of giga-electron volts). This threshold is determined by the laws of energy and momentum conservation and is related to the requirement of losing about 0.14 GeV in forming the rest mass of each pion. For comparison, we note that the energy for the cascade formation and subsequent development of electron showers is hundreds of times lower. This is related to the fact that creating the rest mass of a pair of light particles (electrons and positrons) requires energies of only slightly more than one million electron volts (MeV).

This quarter century, during which physicists intensively studied the processes of multiple particle generation, is characterized by the peculiar competion between specialists of cosmic rays and specialists of the physics of high energy particles produced by accelerators. The upper limit of the energy of cosmic ray particles is practically infinite (it is on the order of a billion times higher than the threshold for multiple pion generation). However, with the increase in energy, the flow of particles decreases catastrophically, i.e., the number of interactions of the corresponding "cost free" cosmic ray particles that are accessible to study diminishes rapidly. The working conditions of the powerful accelerators are more favorable. A peculiar division of labor has developed: an extensive but very approximate survey using cosmic rays, and a detailed, strictly quantitative study of the phenomena using accelerators.

CHAPTER 1. TRACKING THE INVISIBLE

It is Not Always Necessary to See in Order to Detect and Identify Particles /15

Even after the Soviet physicist D.V. Skobeltsin saw tracks of charged particles of cosmic radiation (this was in 1927) with the help of the Wilson cloud chamber, many physicists continued and are continuing to study the characteristics of this radiation with one and the same electronic device. Three different methods exist by which charged particles of high energy can be "sensed" and by which this "sensation" can be translated into the language of electronics.

First, one can let the particle pass through an enclosed volume of gas and make use of its ability to break the neutral gas atoms into electrons and positively charged ions. By introducing special electrodes into a gas vessel and by putting a potential difference across them, one can either simply collect "ready-made" ions at the cathode and electrons at the anode, or ionize new atoms and by this means sharply increase the charge collected at the electrodes (Figure 3). The ionization chamber works by means of the first method, and the gas discharge counter — by means of the second. An externally generated electronic pulse is used to start the counting device in order to register the incident particle, or more precisely, its track. Due to the relatively slow displacement of the charges produced in the volume of the chamber or counter, both of these detectors have poor time resolution* (no better than

* By time resolution is meant not only the precision with which the device determines the instant the particle passes, but also the minimum time interval after which another particle can be registered.

10^{-6} or 10^{-7} sec.) and therefore are hardly used in work with accelerators. /16

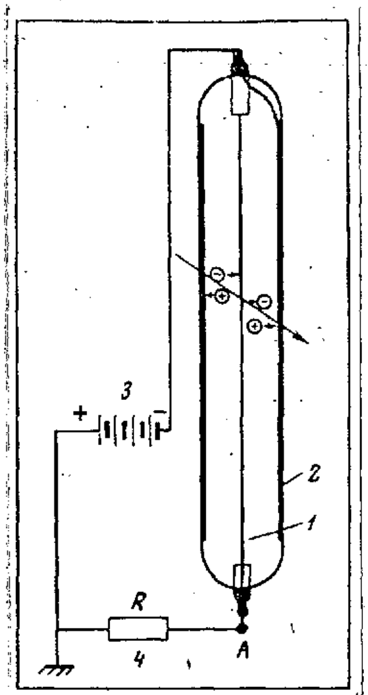

Figure 3. Schematic diagram of the gas discharge particle counter.

Electrons originating with the ionization of the gas are driven by the strong electric field between the anode 1 and the cathode 2 and start an avalanche of new electrons and ions. This leads to the formation of a significant electrical pulse at point A of the external circuit; 3- battery; 4- resistor

In the second method, the particle is passed through a specially prepared transparent solid material having a high efficiency of luminescence, i.e., the ability to transform the excitation energy of the molecules into energy of visible light. Such material is called a phosphor. With suitable organic materials, time resolutions on the order of 10^{-9} seconds can be attained. The light signal in turn is translated into the language of electronics by means of a photoelectron multiplier (Figure 4).

Finally, one can use Cerenkov radiation. This radiation occurs with the passage of a very fast particle through a medium in which its speed is greater than that of light in that medium*. The technology of Cerenkov radiation has attained a high degree of perfection during the last few years. By way of example, one can cite the 5.5 meter long differential isochronous counter

* What is meant here is not the propagation velocity of the light signal in the medium, but rather that velocity which is determined by the delay of the phase of oscillation of the electromagnetic field from point to point on the path of the light ray.

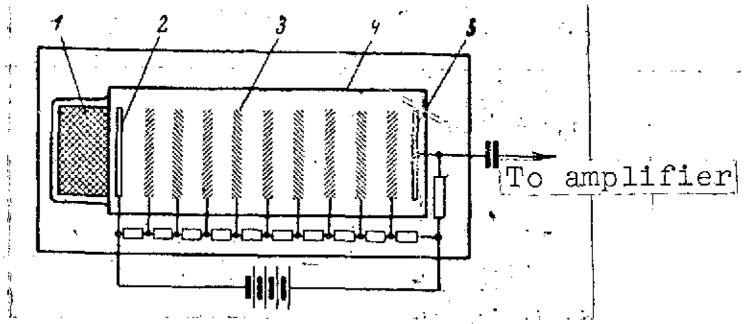

Figure 4. Scintillation (luminesence) counter with photoelectron multiplier (PM).

Energy is lost by an ionizing particle in the material of the scintillator 1; it partially de-excites by emitting photons, which knock out electrons from the photocathode 2; the latter are multiplied on the dynodes 3 of the PM 4 as a result of secondary electron emission and are collected on the collector 5

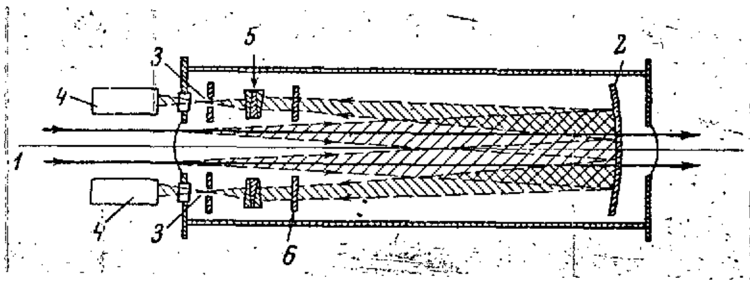

Figure 5. A large gas differential Cerenkov counter in cross-section.

The optical mirror system 2 focuses the Cerenkov light of the particle beam 1 on the diaphragm 3 for a well defined velocity of the particle beam 1; this light is detected by the photomultiplier 4. Tuning to a given velocity is achieved by changing the pressure of the gas, and this requires corrections for chromatic (5) and spherical (6) abberations (the counter was built at CERN)

built not long ago at the European Center for Nuclear Research (CERN). This device can be "tuned" to particles, fixing their velocities to an accuracy of the sixth order, i.e., to one-ten-thousandth of a percent (Figure 5). In order to achieve such /17 time-of-flight resolution with scintillation counters and nanosecond technology*, one would need an apparatus about 100 km long.

In 1961 the Soviet physicists A.I. Alikhanyan, G.M. Garibyan, and collaborators developed still another type of counter based on the phenomenon of so-called transition radiation. This is radiation which occurs when a light but very energetic particle (electron or positron) passes from one medium to another. In contrast to Cerenkov radiation, which quickly reaches saturation as the velocity of the particle increases, transition radiation continues to grow uniformly with the increase of the ratio of the total energy of particle to its rest energy. For electrons or positrons of energies on the order of 1 GeV, it is sufficient to place in their paths a "waffle" of several hundred very thin layers of material with air gaps in order to detect with $\approx$ 50% probability one or more photon quanta of transition radiation behind the "waffle" (Figure 6). It is even easier to use a piece of porous material like foam plastic for this purpose. /18

Electronic and light detectors, possessing very short response times, allow the collection of a huge amount of experimental data, data numbered in millions of micro-events, for a relatively short accelerator operation time. No less significant is the fact that the data from the complex combination of electronic devices can be obtained immediately in a form which can be analyzed on electronic computers. As a result, the preliminary "raw" results of a complex experiment are immediately obtained upon its termination, in spite of the large number of tedious calculations, and can be represented not only in tabular form, but also graphically.

Electronic apparatus is very suitable for simultaneously detecting particles rapidly but in small numbers and when a high

* Remember that this term denotes devices with time resolutions on the order of one-billionth of a second (10^{-9} sec.).

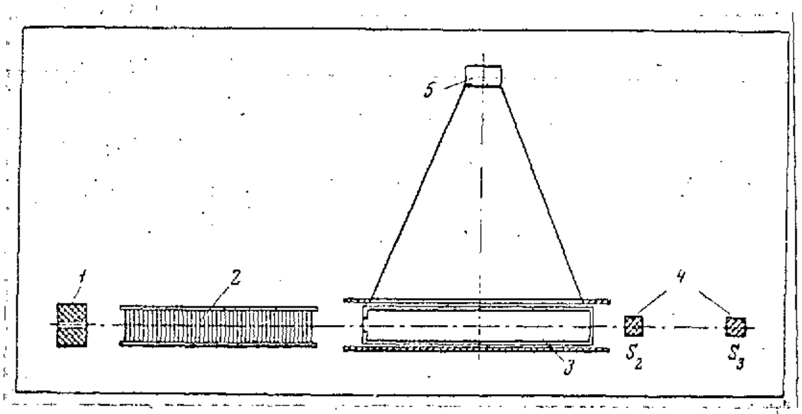

Figure 6. Detector for transition radiation (built at FIAN, i.e., Physics Institute of the USSR Academy of Science). The radiation occurs with numerous transitions of the charged particle from air to the dense medium and out again, and propagates along the trajectory of the particle and is converted to electrons in the volume of the spark chamber; 1- collimator; 2- laminar target; 3- spark chamber; 4- scintillation counters controlling the triggering of the spark chamber; 5- camera

degree of spatial resolution is not required. By using various types of interdependent neutral and charged particles, one can "mobilize" electronic apparatus for counting and measuring (in an indirect sense) neutral particles, in particular, photons, π^0-mesons, and neutrons.

Not only the detection and counting of particles having certain physical characteristics but also the more complex task of "identifying" them can be entrusted to the electronics. To this end, it is often sufficient to determine the mass of the particle, if only approximately. The mass, in turn, can be determined by using any two independent characteristics related /20 to the velocity and mass of the particle. In many cases in working with accelerators, the momentum is determined by the transport of the particles through some type of channel by the use of electromagnetic equipment which focuses the beam of particles of given charge and particles close to a given value of momentum.

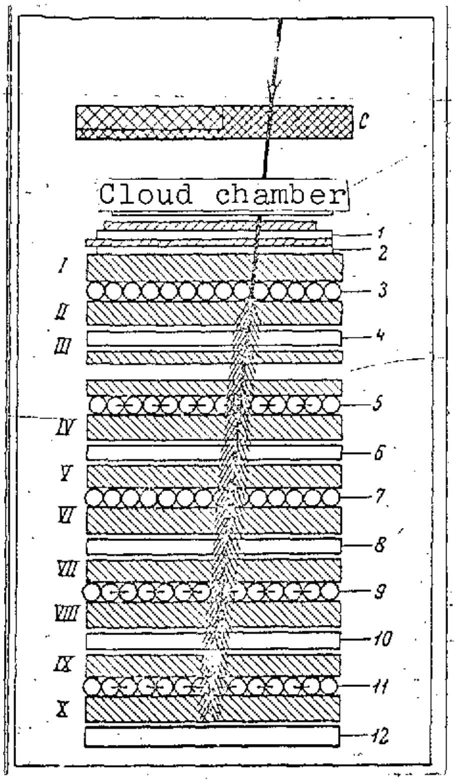

Figure 7. Ionization calorimeter for measuring particle energy (apparatus of V.S. Murzin, L.I. Sarychebii, MSU).

A nuclear-active particle entering from above creates in the target C and in the iron plates I-X an electron cascade, the energy of which is measured by the series of 12 ionization chambers (1-12).

A basic part of such electronic optics is usually the quadrupole lens, a winding which creates a precisely regulated, inhomogeneous magnetic field of annular symmetry. Then as the second characteristic one can use, for example, the velocity, which in turn is determined either by the presence of Cerenkov radiation (as is the case in normal counters), or by the angle of emission of this radiation (as in the differential Cerenkov counter), or by making use of the particle's ionizing ability (as in proportional counters). Instead of velocity, the range of the particle can be used. The range of a particle of a given momentum depends on the specific energy losses due to the ionization of matter.

Several important physics problems, especially in cosmic ray research, require a knowledge of the energy of particles. The energy can be determined by the method of absorption of all the interaction products of the particle with matter. In the case of electrons, one uses secondary electromagnetic processes, which lead to a relatively rapid development and extinction of the avalanche of electrons and positrons. If a heavy, transparent material (lead glass, for example) is used as an absorber, then the total flux of Cerenkov radiation emitted by all the particles of the avalanche can be detected and measured. Such a device is normally called a full absorption spectrometer.

In the case of strongly interacting particles (hadrons), it is necessary to set up an absrober for all the products of the consecutive nuclear-cascade interactions. For this is needed a filter of quite large thickness. In order to measure individual particle energy one can use either the total number of ion pairs produced in a series of ionization calorimeters (Figure 7), which were developed at the Moscow State University (MSU) by V.S. Murzin, N.L. Grigorov and I.D. Rappoport, or the total amount of light produced in a series of Cerenkov counters, as was done by /21
S.A. Azimov, T. Yuldashbaev, and others at the Kumbel' installation in Uzbekistan*. There are huge facilities, which, however, provide an acceptable measurement accuracy on the scale of the microworld. Suffice it to say that with filter thicknesses on the order of 1 kg per cm^2, the areas covered by the ionization calorimeters of contemporary facilities are computed in terms of many square meters. Consequently, the total weight of these filters, usually made of iron, is on the order of tens of tons. Meanwhile, the measurement accuracy of energies in the range 150-200 GeV (about 0.3 erg or roughly 10^{-8} cal.) can reach 20-30%. If we wish to measure such deposited energies with thermal (e.g. calorimeters) instead of electronic devices, then it is necessary to deal with instantaneous temperature increases of the iron on the order of 10^{-15} degrees.

For the determination of a new characteristic dependent on particle velocity but not on its mass, the multi-stage proportional counter, in particular the one used by V.S. Murzin and L.I. Sarychev at the high altitude experimental station on

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* These devices depend on the total absorption of all the light produced in the avalanche and hence are also called a total absorption spectrometer.

Mount Aragats, is very useful. Despite the large spread in the number of ions created by charged particles of a given velocity in the volume of each counter, the collection of pulses from the multi-stage counter is a sufficiently accurate measure of velocity. In such a counter it is possible, as a rule, to distinguish between pions and protons up to energies of 10^{12} eV.

There are other problems, whose solutions depend not so much on the high accuracy of measuring ionizing ability but rather on the possibility of determining (with reasonable accuracy) the coordinates of passing particles and also the time of their passage. With this in mind, multiple-wire proportional chambers have been constructed at CERN (Geneva). Each chamber consists of a relatively light (a weight of about 6 kg), flat, right-angled box of area about 0.5 m^2 within which are strung fine metal wires at a spacing of about 2 mm. Each wire fulfills the function of an independent counter giving a very short (25 x /22
10^{-10} sec) pulse, the amplitude of which is proportional to the ionizing ability of the passing particle and this itself is a measure of the velocity of the particle. Several such chambers, placed in a magnetic field, can provide sufficient information for determining the momentum of the particle by the curving of its trajectory. With a knowledge of a particle's momentum and velocity, it is an easy matter to determine its mass.

How are the Particles Nevertheless Photographed?

In order to objectively retain scenes from human life, we project an optical image of these scenes on a photographic plate and we develop and fix the hidden images thus obtained. In order to just as objectively fix "scenes from the life" of elementary particles, moving at velocities close to that of light, physicists make the particles themselves work. Any charged particle leaves tracks in matter, chains of "damaged", electrically charged atoms and molecules.

Simplest of all is to make the particles "act" within a sufficiently thick layer of photographic emulsions. But after the first ideas of a similar nature were first expressed, in particular as early as 1927 by L.V. Mysovskiy (USSR), about 20 years passed before photoemulsions for elementary particles acquired the sensitivity and stability required by the physicists. In spite of its simplicity and cheapness, the method of photoemulsions has several serious deficiencies. In the first place, the picture of the interacting particles is registered in a volume. It would appear at first glance that this would be better than a flat projection. But on further examination, serious difficulties arise with scanning and measuring the tracks. It is unbelievably slow and painstaking work, which is very difficult to automate. Therefore it is necessary to pass judgement and draw conclusions on the basis of an analysis of several hundred events.

For the study of the microworld, in which all processes are subject to the "caprices" of probability, solid statistical guarantees are necessary, and photoemulsion data leave one with a feeling of dissatisfaction.

Besides this, the nuclear composition of photoemulsions is
very nonuniform and complex. It is true that there are well /23
proven rules for separating out the interactions of the incident particles from the individual, almost free nucleons of the nucleus, but this "almost" can sometimes significantly distort and "blur" the picture of the phenomena.

Photoemulsions also have their merits. The small size of the silver bromide grains forming the tracks of the particles (e.g. 0.1-0.2 microns) allow the examination of the smallest details of an event, yielding high spatial resolution. Using photoemulsions one can even observe the decay of the neutral

π^0-mesons a particle living less than 10^{-16} seconds! This quality of photoemulsions is very valuable when one is dealing with particles of enormous energy, 10^{13} eV and higher. Colliding with stationary nuclei, these particles create very narrow beams of secondary particles, beams whose opening angles are measured in minutes of arc.

The most serious competitor of the photoemulsion for the study of multiple particle production is the bubble chamber invented by D. Glaser (USA) in 1952. Its principle of operation is based on the fact that the ionization of matter by charged particles promotes the formation of bubbles of vapor in a superheated liquid. The liquid is brought to its superheated operating condition by means of a special piston, and then bubbles start to form and grow along the tracks of the particles. When the size of the bubbles reaches about 50 microns, they can be photographed using sufficiently strong illumination (the liquid, of course, is transparent).

Several liquids, one of which is liquid hydrogen whose nuclei are the elementary particles, the protons, are suitable working materials for the bubble chamber. Heavy hydrogen, deuterium, whose nuclei are made of the proton and one neutron, is also used. When it is necessary to study π^0-mesons, one can use their property of practically instantly decaying into photons with the subsequent transformation (conversion) of the photons into pairs of charged particles, electrons and positrons. Heavy liquids, in particular, liquid neon or refrigerating mixtures like freon, are used to guarantee the conversion efficiency. If the process of π^0-mesons formation together with charged pion /25
formation on protons is to be studied, then an external cylindrical container of liquid hydrogen and an internal one containing a mixture of hydrogen and neon are placed in the path of the particle beam. With a carefully constructed device of this type,

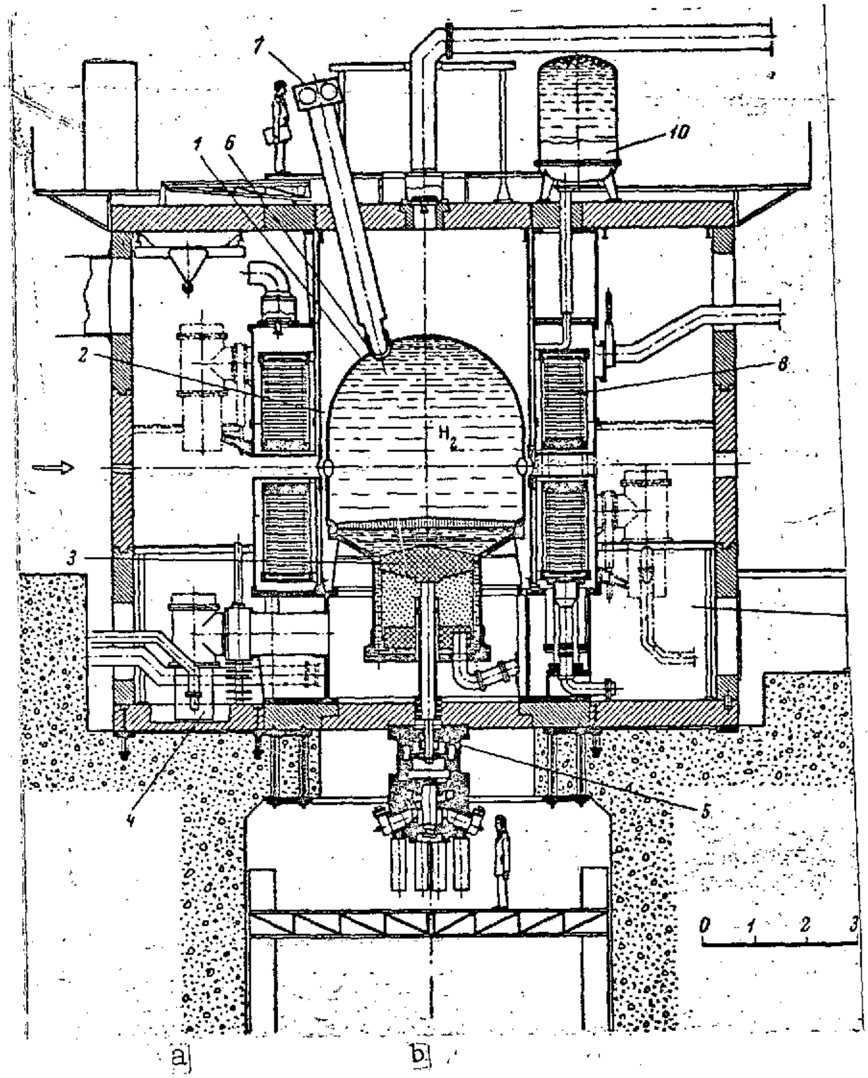
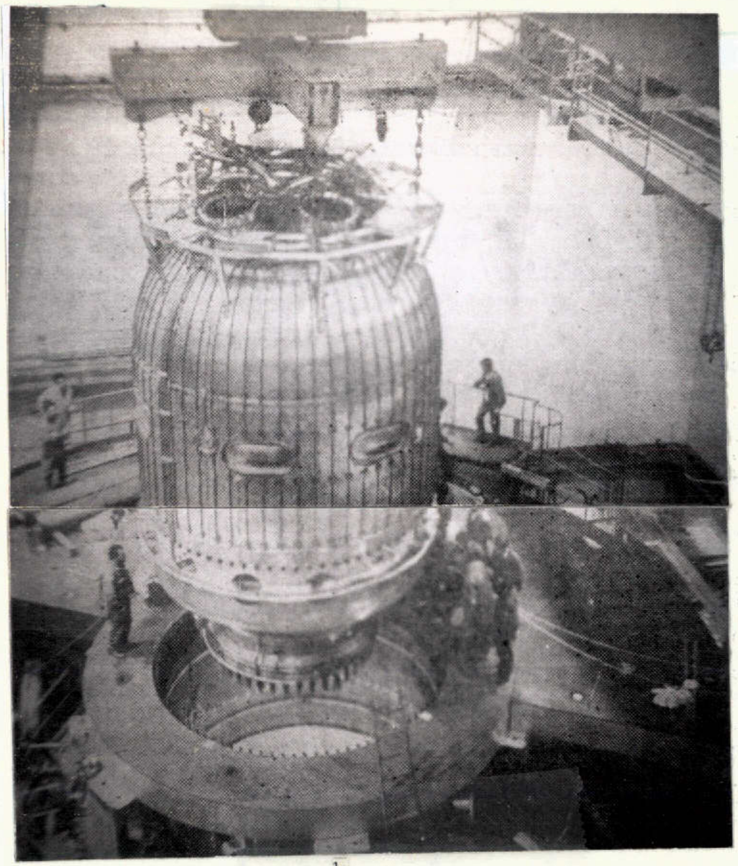


Figure 8. The large European bubble chamber with a useable liquid hydrogen volume of 21.5 m^3; it operates in a magnetic field of 35,000 Gauss (CERN, Geneva)

a) cross section of the chamber: 1- housing; 2- vacuum tank; 3- piston; 4- vacuum pumps; 5- motor of the expansion mechanism; 6- wide angle lens (of the fish-eye type); 7- camera; 8- superconducting windings; 9- liquid nitrogen; 10- liquid helium. Scale at bottom-right
b) installing the chamber housing in the vacuum tank (see page 26)



b

it is almost impossible to distinguish the boundaries of the two chambers on the photographs.

Current bubble chambers are very large. They can be filled with many cubic meters of liquid hydrogen or heavy liquids (Figure 8). These chambers are placed between the poles of huge electromagnets. Recently magnets have been made with superconducting coils. By bending the particle trajectories in magnetic fields on the order of 10-20 thousand Gauss or even /26
higher, their momenta can be measured with good accuracy (1-2%).

These experiments are expensive. Multimillion dollar equipment expenses are increased even further by the need to analyze the bubble chamber stereophotographs on complex automatic machines, which work in conjuction with powerful electronic calculators in order to provide the high productivity necessary for the measurements. The development of analysis programs for the measured data also demands much effort. In return, the computers produce nearly final physical results, even estimations of the plausibility of various hypotheses or the character of observed processes, the quantity of invisible (neutral) particles produced, etc.

The productivity of current bubble chambers is measured in terms of many thousands of photographs (even a special unit of the number of photographs, the kilophotograph, has been coined). In 1972 at CERN a singular record has been set: 20 million photographs from the 2 meter hydrogen chamber (it is true that only a relatively small number of photographs, not more than 10%, are of interest to the physicists and are analyzed).

In spite of all its undisputed merits, the bubble chamber is not "sinless"; it is nearly totally devoid of "memory". The misfortune consists of the fact that the particle tracks consist of individual ions which exist in a free state for less than 10^{-10} seconds in a neutral liquid. Within this time it is currently impossible to bring about by mechanical means the drop in pressure required for the formation of gas bubbles in the material. As a result, the signal for triggering the piston must be given in advance, synchronized in time with the pulsed mode of operation of the accelerator.

In addition to its purely practical drawbacks (complexity of construction, high cost, large size, explosion hazard), the bubble chamber suffers from one fundamental shortcoming. It is a device which is not sufficiently "operative"; it requires several (up to 10) milliseconds to lower the pressure and develop gas bubbles along the particle tracks and still additional tens (even hundreds) of milliseconds to return to the initial state.

Because of the impossibility of anticipatory control, the bubble chamber is not used for studying processes produced by cosmic rays. In this case, the physicists' old friend, the cloud chamber, comes to the rescue. This device was developed as early as 1912 by C. Wilson and is called the Wilson chamber in our country (USSR). As in the case of the bubble chamber, a piston is also used to reduce the pressure at the required instant, but the drop in pressure produces the opposite effect, the condensation of gas molecules to liquid surrounding the chain of ions of the particle track. Since the ions have a much longer lifetime in a gaseous medium than in a liquid, the "memory" of the cloud chamber is a million times better. It can start on the "tail", after the particle passes through the chamber. All the problems associated with creating a magnetic field-illuminating the tracks of particles, photographic them, analyzing the photographs, miscalculating the measured data-remain, in principle, the same. However, even with large apparatus, physically interesting phenomena are only rarely observed — a few times in a hundred in the best cases. /27

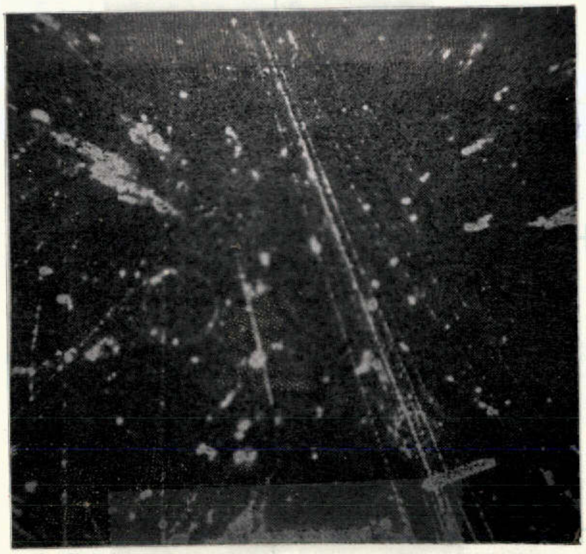


Figure 9. Photograph of multiple particle production in a cloud chamber with a magnetic field (Tyan'-Shanskii station FIAN). About 20 charged pions are formed in the LiH target above the chamber. The primary energy (measured by an ionization calorimeter) is 820 GeV

A picture of such a phenomenon is reproduced in Figure 9. It shows the formation of 20 charged pions in the target above a cloud chamber. Because of the high energy of the primary particle, the bundle of secondary particles is narrow. This makes particle separation and accurate angle measurements difficult. Many tracks of "extraneous" particles of low energy are visible in the photograph. /28

A disadvantage of using the cloud chamber results from the low density of the gas as compared to that of a liquid. As a result, plates of heavy material have to be put inside the chamber (or placed immediately above it). They serve as nuclear targets for efficient "bombardment" by high energy particles. What occurs within the plates in not visible; moreover, it is practically impossible to work with solid hydrogen (the cloud chamber is "afraid" of drops in temperature). Thus, composite substances must be used, like lithium hydride (LiH). Therefore, experimental set-ups for cosmic rays using cloud chambers are not as neat as in the case of bubble chambers using accelerators.

Visible and Invisible Sparks Join in the Task

In 1957 a new type of device was constructed, the spark chamber, in which the ion tracks of particles become visible by means of the development of an avalanche-like electrical discharge in a gas between two conducting plates, the electrodes (Figure 10, a). The spark chamber is operated with the aid of two or more particle counters placed near it. With the passage of charged particles in the required direction, the electrical pulses from the counters pass through a special coincidence unit and switch a high voltage supply to the electrodes of the chamber. The electrons remaining after the passage of the particle move in a strong electric field and start a spark discharge where the particle passed. The spark chamber in itself is very simple. The basic problem is the construction or acquisition of a high voltage source (tens, and sometimes hundreds of kilovolts in the case of wide gap electrodes).

The operating cycle of such chambers can be reduced to 10 milliseconds, and the "memory" time — to 1 microsecond. The latter is important for operations using accelerators, since it makes it possible to separate out the undesired background of extraneous particles. /29

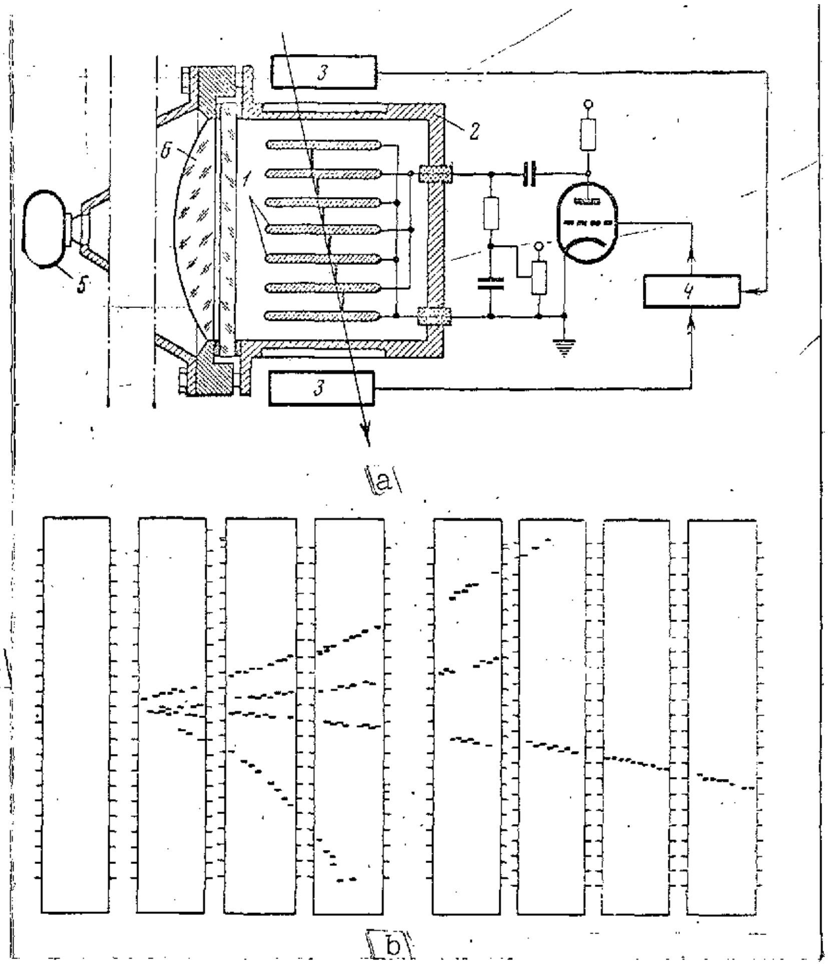


Figure 10. Spark chamber:

a) schematic diagram of the chamber: 1 — electrodes; 2 — housing; 3 — controlling counters; 4 — coincidence unit; 5 — camera; 6 — lens; b) an event recorded in a spark spectrometer (consisting of 8 chambers) of the type "Omega" (CERN) with subsequent television transmission of the data and analysis by computer

The gain in operating frequency is unfortunately accompanied by a loss in spatial resolution in determining particle coordinates. The accuracy of data obtained by spark chambers is limited to 0.2 - 0.3 mm. Therefore, in high accuracy measurements of angles (e.g., in studying the elastic scattering of particles), it is necessary to use a series of spark chambers, each separated sometimes by tens of /30 meters. However, in studying rare events in cosmic rays, this deficiency can be corrected by supplementing the spark gaps with "stacks" of nuclear photoemulsions. Then the sparks serve only to indicate the presence of a particle; and its coordinates and, consequently, its angle of deflection in the magnetic field, as well as its momentum obtained from these measurements, are made more accurate by means of the photoemulsion measurements.

For relatively simple problems in which particle coordinates do not have to be recorded with high accuracy, and for whose solution the spark chambers are suitable, the recording of particle tracks is substantially simplified. The process of photographing the chamber on film with the subsequent measurement of the sparks on the photographs can be replaced by measuring the spark position by the time of arrival of the sound corresponding to the "microlightning" in a special electro-acoustic receiver. Often soundless, purely electrical methods of measurement are used: by setting up a coordinate grid of fine wires, one can record the electrical signals induced in these wires by closely passing particles.

The basic virtue of both variations of electrical recording of sparks is the extensive possibilities of automating the analysis of experimental data using computers. No less important is the characteristic of recording the data at a distance, especially under experimental conditions (e.g., in an experiment in space) in which it is not suitable for some reason to transport exposed photographic film to the laboratory in order to analyze the data.

However, automation is also possible with photographic methods of obtaining information. To this end, images of the sparks are projected to a transmitting television tube, and the subsequent analysis is made by means of an electronic survey (scanning). As with good household televisions, sufficiently clear images are obtained without the use of photochemical processing (Figure 10b).

CHAPTER 2. ELASTIC SCATTERING AND THE STRUCTURE OF ELEMENTARY PARTICLES

Electron "Supermicroscope" and the Structure of Nucleons

In order to examine the external appearance of very small objects, we use a microscope, which allows us to learn not only their form, but also their color. But what determines color? Merely the ability to absorb, reflect, and refract light waves of different wavelengths. Thus, for example, the color spectrum of the rainbow results from dispersing the Sun's light into waves of various wavelengths, reflected from water drops at various angles. /31

For the study of the internal structure of matter, the construction of its crystal lattice, for example, there exists the method of X-ray structural analysis. It is based on the fact that electromagnetic waves, scattered by the atoms of a material, undergo diffraction, i.e., they reinforce one another in specific directions and cancel one another in other directions. This depends on the distance between the atoms of the lattice (or more precisely, on the relationship between this distance and the wavelength of the incident waves).

By using this phenomenon of diffraction of electromagnetic waves, one can obtain a very good three-dimensional picture of matter with high spatial resolution, but in this case the question of color loses all meaning. However, the X-ray method can be modified somewhat by using fluorescent analysis. This is based on the fact that matter, having been irradiated by X-ray "light", starts to emit its own radiation of wavelength characteristic of each of the chemical elements.

But, in this case, each quantum is scattered with a change in frequency and energy. Such a process is called inelastic scattering.

And what should be done in order to progress from an analysis of the crystal structure of matter to the analysis of the even finer state of its atomic nuclei or even individual nuclear /32 particles, the nucleons? Let us recall that there is an inverse relationship between the wavelength of light and its frequency and, consequently, also the energy of each quantum. In order to investigate fine structure, it is necessary to use very high energy quanta as the "X-ray" tool. For observing very small particles (e.g., virus particles), the optical microscope is replaced by the electron microscope, which uses quanta of energies of 20 - 50 thousand electron volts (KeV). The corresponding wavelengths are tenths of an Ångström (1 Ångström = 10^{-8} cm). A researcher can even more easily increase the resolving power of this device if he has a high energy electron accelerator at his disposal. However, while the electron microscope provides a gain of one hundred over the optical microscope, the resolving ability, i.e., the energy of the quanta, must be increased by a factor of several million in order to observe the atomic nucleus.

Such was the logic of the research published in 1958 for the first time by the group of R. Hofstadter (U.S.A.), who subsequently received the Nobel Prize in physics for this work. Having an accelerator capable of accelerating electrons up to 1 GeV at his disposal, Hofstadter began to investigate the character of the angular distribution of electrons scattered elastically from first the complex nuclei of various elements, and later from the two simplest nuclei, the nuclei of normal hydrogen (protons) and heavy hydrogen (deuterons). Assuming with complete justification that both the proton and the neutron, which together with the former makes up the deuteron, are spherically symmetric, Hofstadter reduced the problem to a one-dimensional one. He studied the intensity of the electron scattering only as a function of the zenith angle θ, and paid no attention to the azimuthal angle ϕ (Figure 11a), considering the distribution in ϕ to be uniform.

In order to estimate the suitability of electrons as tools for investigating other particles, one must realize that to a good approximation they can be considered as material particles. Corresponding to the experimentally well verified laws of quantum electrodynamics, the process of scattering electrons from protons can be represented by the symbolic diagram first introduced by the American physicist R. Feynman (Figure 11b). At some instant of time (this instant corresponds to the branching point of the lines, the so-called vertex), the electron emits a quantum of the electromagnetic field, which is then absorbed by the proton. As a result, both particles experience a recoil, the scattering. In this case, the photon is virtual in contrast to the usual free photon. In order to elucidate the concept of virtualness, we must turn to the theory of relativity, in which

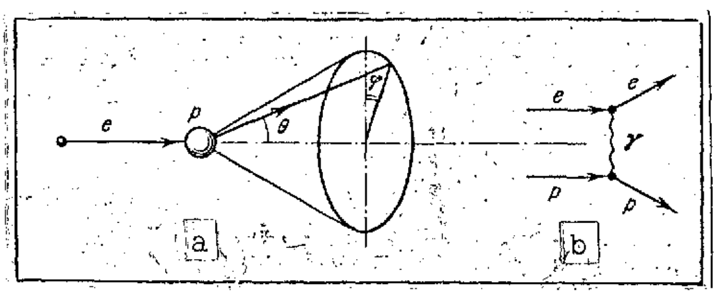


Figure 11. Elastic scattering of an electron (e) on a proton (p):
a) diagram of the scattering: θ — zenith angle; ϕ — azimuthal angle;
b) Feynman diagram for ep-scattering with virtual γ-quantum exchange

/33

the relationship between the energy E and the momentum p of a free particle is derived,

$$E^2 - p^2c^2 = m_0^2c^4,$$

where m_0 is the rest mass, and c is the velocity of light. For particles in a bound state, i.e., in a state of interaction with other bodies (as, for example, an electron in a solid body), the same expression is valid if a negative quantity, U^2, is added to the right hand side of the equation. This term, as if it were "camouflaged" part of the energy, can be combined with the term m_0^2 to form a new quantity $(m^*)^2$, which can be considered as the square of a generalized mass. It is important that, in the case of sufficiently high binding energy U, the square of the generalized mass $(m^*)^2$, can become negative and, consequently, the total mass can become imaginary. It is often more convenient to introduce the quantity $k^2 = (m^*c^2)^2$, which serves as a good quantitative measure of the binding of the particle and is called its virtualness. It is customary to say that a particle whose virtualness is equal to the square of the rest engegy, $(m_0c^2)^2$, is on the mass shell. If the particle is "off the mass shell", then it is in the category of virtual particles.

In accordance with the fundamental conclusions of quantum mechanics, the departure of the particle from the mass shell for a time Δt, and the related uncertainty of its energy state ΔE must obey the relation: /34

$$\Delta E \cdot \Delta t \geqslant h,$$

where h is Planck's constant. If one considers by way of example the virtual pions, which provide the interaction of nucleons within the nucleus, then Δt is about 10^{-23} sec. This infinitesimally small value gives an idea of the characteristic duration of virtual processes.

If the virtual particle is subjected to any external influence, we can return the mass m^* to its initial value m_0 and, in the process, convert the virtual particle to a free one.

According to the results of Hofstadter's experiments, the problem of scattering an electron at a given angle θ from a proton and a neutron (or more precisely, the effective scattering cross-section, i.e., the probability referred to one particle) decreases with increasing angle faster than in the case of scattering from electrons. This difference is expressed quantitatively by the product of the "electron" probability and a factor called the form factor, which depends on the virtual photon. By this term, physicists wish to say that in contrast to point-like electrons, protons and neutrons have a definite form; they are "smeared" out in space over some small region (this is a "smearing" of not only the electric charge, but also the magnetic moment intrinsic to the proton as well as the neutron).

In order to elucidate the very important concept of the "form-factor" of an elementary particle, we must consider one of the basic assumptions of quantum mechanics, the uncertainty principle. Any microscopic object has an uncertainty ("smearing") of position in space Δx and an uncertainty in momentum Δp, and the product of these uncertainties is never less than a certain fixed value (equal to Planck's constant h mentioned above). If the proton and neutron were point-like particles like the electron, then they would be "smeared" out more (which can be calculated a priori) in interacting with electrons by means of virtual pho- /35
tons as a result of the recoil effect. The more virtual the photons, the more this "smearing" would be. In electron

scattering experiments, the recoil turns out to be less strong than expected (this is expressed most of all in the decreased scattering probability of electrons at large angles). This disagreement is explained by the fact that electrons can penetrate "within" the real proton or neutron, which possess a finite extension and a definite geometric form.

Experiments show that the proton has a "smeared" electric charge (positive) of a mean radius of about $0.8 \cdot 10^{-13}$ cm. In addition, its magnetization, its magnetic moment (Figure 12), is "smeared" to approximately the same extent. Moreover, the neutron, on the whole electrically neutral, has been found to have a small charge alternating in sign. And the important thing is that a magnetic moment has been observed, which is, on the whole, negative and is just as strongly "smeared" out as the positive moment of the proton. The existence of electric and magnetic nucleon form-factors, which sharply decrease with increasing distance from the center and which are clearly not point-like, can be visualized as if each nucleon is in a unique dynamic equilibrium, continuously exchanging virtual field quanta, mesons, with other nucleons.

In contrast to light quanta (photons), which are emitted by a non-uniformly moving electric charge, the free quanta of the meson "cloud" of the nucleon possess a finite mass. Based on the fact that the effect of the nuclear force is sharply limited in space*, an approximate estimation of this mass was made as /36
early as 1935 by the Japanese theorist H. Yukawa. The very same

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*For a rough estimate of the π-meson mass, m_π, based on the maximum radius of the nucleon exchange interaction $r_0 \sim 3 \cdot 10^{-13}$ cm, the quantum mechanical uncertainty relation $\Delta E \cdot \Delta t \sim h$ can be used, taking $\Delta E \sim 3m_\pi c^2$ for the energy uncertainty, and $\Delta t \sim r_0/c$ ($c = 3 \cdot 10^{10}$ cm/sec), and taking into account that $h = 6.6 \cdot 10^{-27}$ erg/sec $= 4 \cdot 10^{-15}$ eV/sec.

idea of the exchange nature of the nuclear force was expressed even before this by the Soviet physicist I. E. Tamm.

Concerning the Use of Physically Meaningless Values of Quantities

The structure of elementary particles observed with the help of the "super electron microscope" led the physicists to some very profound thoughts. According to their conceptions, the nucleons remained elementary as before, i.e., physically indivisible particles but of known extent. The very concept of structure implies, in principle, the possibility of separating nucleons into their composite parts. One means of doing this, as was mentioned previously, is to expend enough energy to convert a virtual meson into a real one, i.e., into a free meson.

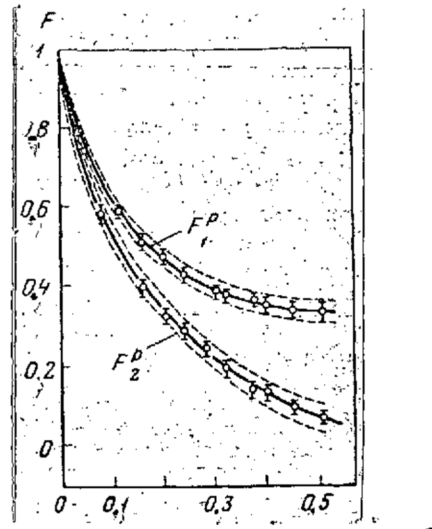

Figure 12. Proton form-factor (scattering probability with respect to a point target: $|t|$ — square of the momentum transferred to the electron; F_1^p — electric; F_2^p — magnetic form-factor

A second method is the detailed study of elastic scattering of already created mesons on nucleons. For this purpose, the electron accelerator must be replaced by a meson "factory" (the name given to proton accelerators with powerful beams of secondary mesons). Having a source of artificial cosmic rays, the proton accelerator, one can, for example, create with the aid of these particle accelerators beams of negatively charged pions by "bombarding" suitable targets with protons, and then focusing the produced pions on liquid hydrogen targets.

Now let us consider how to mathematically describe the process of elastic scattering of particles, and how to characterize it in terms of physical quantities. This process is most simply described in the center of momentum (c.m.) system, i.e., in that system in which the particles move toward each other with the same magnitude of momentum p, or for equal mass particles — with the same speed v (p = mv, where m is the mass of each particle). /37 Since before the collision the particle momenta are equal in magnitude and opposite in direction $(\vec{p}_1 = -\vec{p}_2)$, then after the collision this same relation must hold $(\vec{p}_1' = -\vec{p}_2')$. The result of the collision can be described by the probability W that each particle is scattered at the same angle θ. The probability W is a mathematical function of two quantities. One is the magnitude of the incident momentum p (its direction plays no role), or, equivalently, the total energy of both particles. The second quantity is either the scattering angle θ or the absolute value of the vector difference of the initial and final momenta $\Delta\vec{p} = |\vec{p}_1' - \vec{p}_1| = |\vec{p}_2' - \vec{p}_2|$, which is equal to the momentum transferred by the particles. If the magnitude of the transferred momentum is sufficiently large, the scattering angles must decrease (all other things being equal) in inverse proportion to the initial momentum of the colliding particles*.

For convenience, another quantity, the complex quantity $A = A_1 + iA_2$, which is called the scattering amplitude probability (or simply the scattering amplitude), is introduced in place of the probability. The probability and amplitude are related by the equation $W = A_1^2 + A_2^2$. It happens that even the imaginary part of the scattering amplitude is important for those scattering situations in which each of the colliding particles can act

*In fact, for elastic scattering $\sin\theta = \Delta p/p_1$, and, as a result, of small angles, $\sin\theta \simeq \theta$.

as a black (absolutely absorbing) ball. Here one encounters for the first time the inseparable link between absorption as an extreme case of the inelastic interaction of particles and their mutual elastic scattering: wave absorption close to an obstacle causes wave distortion and, consequently, the possibility of elastic scattering of any particles having a wave nature. The real part of the scattering amplitude is related to the refraction of incident waves in a partially transparent ("grey") ball, the target.

The total energy is also not very convenient for the theoreticians. It is more appropriate to be concerned with the square of the energy, or rather with the square of the total momentum $s = (p_1 + p_2)^2$. Finally, instead of the transferred momentum, they introduced the square of the difference of the momenta, but with opposite sign $t = -(\vec{p}_1 - \vec{p}_2)^2$. In this fashion, /38 the process of elastic scattering is described by the function A of the variables s and t, the former always positive and the latter always negative.

The relative angular momentum l of the colliding particles is also included in the description of the scattering process. This can, according to quantum physics, only assume discrete values — integer or half-integer in units of Planck's constant An additional consequence of quantum physics is that the higher a particle's energy, the larger the number of waves associated with it. These waves have increasing values of l, and can play an "active" role in the scattering process.

We now begin a discussion of a quite abstract but very productive physical-mathematical model which theoretical physicists have begun to elaborate starting with an idea of the Italian

T. Regge. In honor of the originator of the initial idea, every facet of the work has acquired the jargon-like qualifier "Reggeized". One postulate of this theory is that the angular momentum of a virtual particle can be considered as having any complex value.

The idea of this generalization becomes natural if one recalls the parallel cited above between virtual and strongly bound particles. If a virtual particle can be compared, for example, to an electron bound in a hydrogen atom, then it is necessary to consider that, in addition to its inherent moment (spin), it must have an "arbitrary" angular momentum.

As the fundamental equation of quantum mechanics for atoms (the Schroedinger equation) shows, this arbitrary moment (and, consequently, also its total moment, which can be called the bound particle spin) depends on the binding energy U, and assumes integer values for completely specified values of U, called the energy levels of the atom. From here it is not difficult to progress to the general concept of virtual particle spin. By continuously changing the energy U, the value of the spin must continuously vary (including complex values), since the spin is a single-valued function of total energy and mass. The value of the mass assumes integral (positive) values just when the virtual particle "decides" to become free. In this way, one arrives at /39 the concept of families of related (in all physical characteristics except mass and spin) particles, which seem to be excited states of various "parent" particles possessing a definite internal structure.

The second postulate includes the assumption that the amplitude of mutually scattered particles a and b must always be an analytical function of the arguments s and t. This means that a detailed study of the behavior of this function even for small changes in the quantities s and t allows one, in principle, to determine its behavior over the entire range of possible values of s and t of the elastically scattered particle a. It is also useful to consider absorption of the corresponding anti-particle $\bar{a}$ (annihilation) with the subsequent emission of the anti-particle $\bar{b}$ (instead of the absorption of particle b) and the particle a. The consideration of such an additional annihilation "channel" of the reaction allows a crossing-over into the region of negative values of the energy variable s and positive values of the momentum variable t.

For the process of elastic scattering negative energies and negative squares of transferred momenta, i.e., positive values of t, has in itself no physical meaning (in particular, a positive value of t could only be attained if the cosine of the particle's scattering angle θ became greater than one). However, the theory in its entirety allows the attainment of an exquisite mathematical description of elastic scattering, the prediction of several characteristics of this process which at first glance appear extremely surprising, the discovery of the profound internal relation with the process of exciting elementary particles to resonance states, and also the prediction of the existence of definite classes or families of excited states which are characterized by specific sets of discrete characteristics (quantum numbers) and specific, regular relationships of masses and angular momenta ((spins).

A surprising feature of elastic scattering that is well explained by Regge theory is, in particular, the decrease of transferred momentum in several important cases (proton-proton scattering) of scattering as the incident energy of the colliding particles increases. This peculiar situation consists of the

fact that at first glance the scattering process should be analogous to the diffraction of X-rays in crystals, but the diffraction pattern does not depend on the energy of the X-ray quanta. /40
It is determined only by the geometric parameters (size) of the crystal lattice. In addition, it seems as if the colliding protons slightly "expand" with increasing energy, and the angles of their mutual diffractive scattering decrease faster than the simple increase in particle momenta would require.

Thus, for example, in increasing the proton energy from 3 /41
to 60 GeV (a factor of 20), its effective size increases by two.*

It is interesting to compare the information about the "form" of the proton obtained with the help of the electron, which serves as an ideal point "probe", with that obtained from elastic proton-proton scattering. In the latter case, one can foresee that the form-factor of the proton will appear twice, because the proton is simultaneously both the source and the absorber of virtual particles. Figure 13 indicates that these expectations begin to be confirmed as the energy approaches 25 GeV. Actually, in order to make the transition from the characteristics of a point particle to those of a real particle, it is necessary to multiply the point particle cross section twice by the square of the electromagnetic form factor of the proton and, as a final result, introduce the fourth power of the form-factor.

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*By effective size we mean that size which, according to the uncertainty relation, is inversely proportional to the mean value of the momentum of the recoil particle in the process of its scattering, since no other method of measuring the size of elementary particles exists.

Resonances — New Particles or New States of Known Particles?

In 1952, the renowned Italian physicist E. Fermi at the University of Chicago, together with his colleagues, began a series of scattering studies of positive and negative pions on protons. The scheme of their experiments was very simple (Figure 14a), since the energy of the pions at that time did not surpass 150 MeV, and nothing but elastic scattering was expected. Three years later, when the Brookhaven Cosmotron came into operation, Lindenbaum and Yuan continued these experiments in a significantly more refined situation. Thus, physicists were able to advance into the region of significantly higher pion energies (e.g., up to 2 GeV). In addition, they were able to measure not only the probability of scattering at given angles (45, 90, and 135°, as in Fermi's experiments), but also the total probability that a proton striking the target would scatter at any angle.

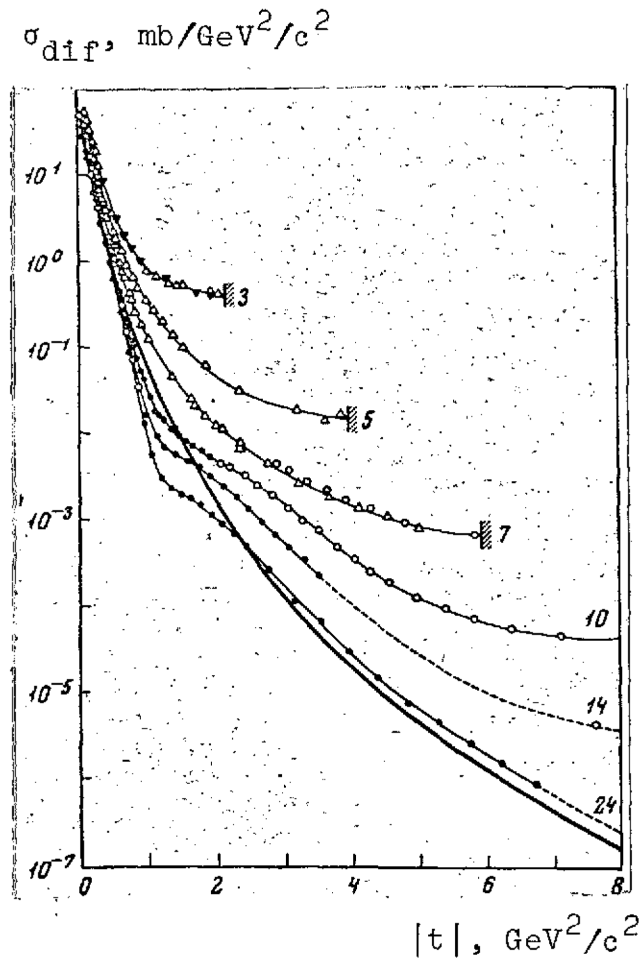

Figure 13. Distribution of transferred momenta for the elastic scattering of protons on protons (differential cross section σ_{dif}):

Numbers to the right of the curves indicate energy of the incident protons (GeV). The calculated curve (heavy) was obtained from ep-scattering

The total probability W is usually expressed in terms of the total cross section of the process σ_t: /42

$$W = \frac{1}{\sigma_t N_0}.$$

Here, N_0 is the number of atoms of hydrogen in each square centimeter of the target "bombarded" by the pion beam. If the pions striking the target were material points, then the value of σ_t would be determined by the lateral cross section of each of the opaque balls, which is equivalent to the scattering center, the proton. But the incident pion possesses wave characteristics, e.g., a wavelength $\lambda = h/p$, where p is the particle momentum. In this case, as shown by quantum physics, the maximum possible cross section is expressed by the value $\sigma_t = \lambda\ (2I + 1)$, where I is the angular momentum of the scattered particle (in units of Planck's constant, and λ — its wavelength.

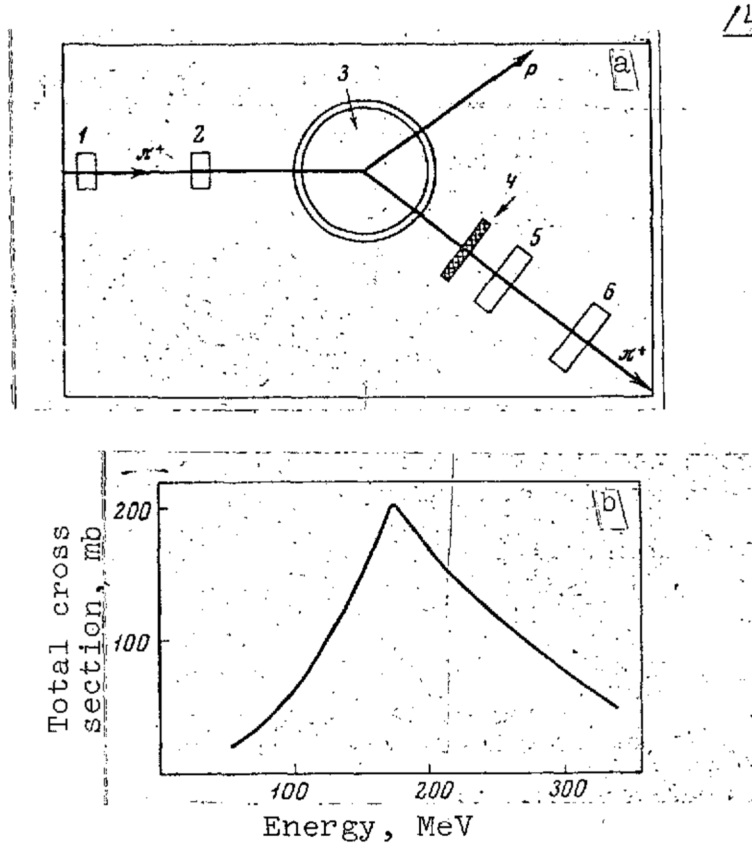

Figure 14. a) Diagram of the experiment for elastic π^+p scattering:

1, 2 — incident particle counters; 3 — liquid hydrogen; 4 — lead filter; 5, 6 — scattered particle counters /43

b) Experimental results showing the resonance character of the process

One of the fundamental results concerning π-mesons with energies up to 350 MeV is shown in Figure 14b. It is evident that the cross section reaches a sharp maximum (about 200 millibarns, or $2 \cdot 10^{-25}$ cm^2)* near 195 MeV. This value is close to the theoretical one if the angular momentum of the scattered wave is considered to have the value 3/2. It was also shown that the scattered wave is distinctly different in phase from the incident, and this difference gradually increases with pion energy until it reaches 90°, where the cross section is maximum.

It is possible to draw an analogy with the resonance transfer of oscillatory motion between two pendulums of different lengths suspended from the same string. When the pendulum coincides longitudinally with the "driving" pendulum (which is set swinging by an external force), its amplitude of oscillation is maximum and its phase is different by 90° (when the "driving" pendulum is maximally deflected, the "driven" one is passing through the vertical position).

Several years later, in 1959, a group of physicists from the Lawrence Radiation Laboratory (U.S.A.) (G. Chew et al.) made the hypothesis that the resonance state of several strongly interacting particles in nature is by no means limited to this one case. Having analyzed in detail the results of Hofstadter on the electromagnetic structure of protons and neutrons, they came to the conclusion that these particles have meson clouds consisting of roughly 25% individual virtual mesons. Systems consisting of pions resonantly interacting in twos and threes must contribute significantly to this "cloud".

Shortly thereafter, a group of physicists from the same lab, under the leadership of L. Álvarez (subsequently honored with

*In nuclear physics and elementary particle physics, the barn (1 barn $= 10^{-24}$ cm^2) is sometimes used as the unit of measure of the cross section; but much more often, the millibarn (1 mb $=$ 10^{-27} cm^2) is used.

the Nobel Prize) carried out a successful experimental search for ternary systems. These scientists studied, with the aid of the hydrogen bubble chamber, the process of annihilation of protons and antiprotons, which were discovered shortly before. They measured the momenta and angles of emission of charged pions created in the annihilation. They paid particular attention to those 800 events in which 4 charged pions emerged, and from the relation of total energy and momentum conservation, they anticipated the presence of an additional neutral pion (π^0). Knowing (from the same law of conservation of energy and momentum) the vector value of the momentum of the π^0 particle, they calculated the distribution of the so-called effective mass of all three-body systems (π^+, π^-, π^0), which is given in Figure 15. The energy that one is concerned with here is measured in the center of gravity of the bound π^+, π^-, π^0 particle system, after whose decay are obtained the momenta of the free π^+, π^- particles observed in the experiment and the calculated momentum of the π^0. It is necessary to remember that the energy E is related to the mass M_{eff} (called the effective mass) by Einstein's equation $E = M_{eff}\ c^2$ (c is the velocity of light). A small group of separate events (whose mass M_{eff} measured in units of energy is close to 790 MeV) stands out in Figure 15 from the /44

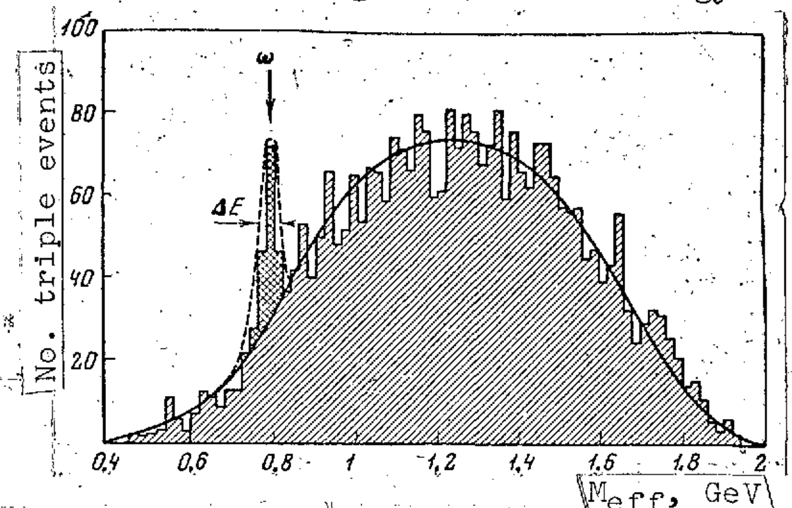

Figure 15. Separated ω-resonance on the effective mass M_{eff} distribution of the three pion system ($\pi^+ + \pi^- + \pi^0$): ΔE — full width at half height of the resonance

background of the smooth curve of the overall distribution of effective mass. The assertion was made that just in such instances a momentary formation and disintegration of a particular resonance system of three pions, called the omega (ω^0) resonance occurs. From the width ΔE of the subsidiary peak on the histogram* of the mass distribution, treating this width as an uncertainty in energy (that also means in mass) of the ω^0-resonance, its life-time τ can be calculated. From the quantum mechanical uncertainty relation

$$\Delta E \cdot \tau \simeq h$$

one gets $\tau \sim 10^{-22}$ sec.

Another bound resonance state, this time a pair of pions called the rho-resonance (ρ) was analogously discovered (but having started from other processes). The mass of the ρ-resonance was found to be equal to 765 MeV, and its life-time roughly 10 times shorter than that of the ω-resonance.

The measurement of the effective mass of a two-particle resonance by means of its decay products is, in general, equivalent to measuring the energy of the resonance maxima in the elastic scattering cross section of the same particles. This can be verified by placing the successive peaks of the curves of the energy dependence of the total π^+p and π^-p scattering cross sections on the "spikes" of the curves of effective mass distribution of "suitable" reactions of multiple pion production in inelastic interactions of nucleons (Figure 16). /45

*A histogram is a broken line, each horizontal segment of which has an ordinate equal to the number of events which has a value of the measured quantity within the interval given on the abscissa.

All the resonance peaks in Figure 16, designated by the symbols Δ and N, correspond to the specific effective masses of the resonances given in the brackets. In contrast to the meson resonances considered above, all these are commonly called baryon resonances since they include a heavy particle, a baryon (in this case, a proton).

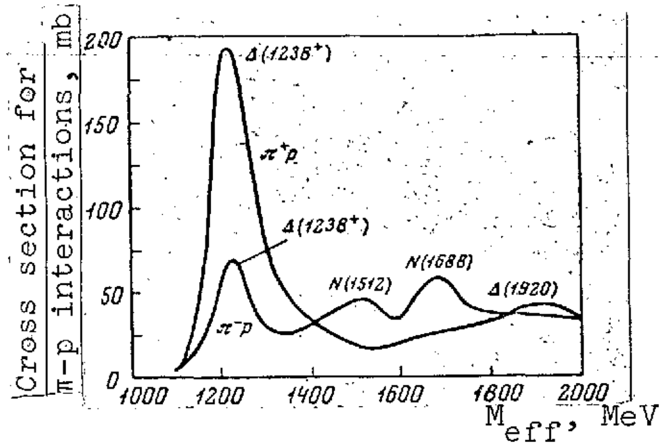

Figure 16. Relation between the masses of the resonances and the peaks of the total cross section for elastic scattering of π^+ and π^- mesons on protons

By comparing the effective masses of the resonance states of various combinations of particles, one can see that very frequently one and the same resonance state can decay in different ways. For example, the well known neutral resonance η^0 (eta particle) with mass 594 MeV, decays 39% of the time into 2 γ-quanta, 30% of the time into 3 π^0 mesons, 23% of the time into π^+, π^-, and π^0 mesons (similar to the ω particle), and it has still three or four more ways of decaying. As a result, the lifetime of the η^0 resonance is two orders of magnitude smaller than that of the π^0 meson. /46

The various internal characteristics, the quantum numbers (of the angular momentum type) of the resonances are just as clearly and unambiguously defined as those of the "normal" unstable particles (in particular, the set of quantum numbers determines all the possible decay modes). The conclusion suggests itself that the distinction between the concepts of "elementary particle" and "resonance state of several interacting particles" practically does not exist. They are physical micro-objects of the same type. There is a much more important difference, for example, between baryon particles and resonances, on the one hand, and mesons, on the other, since the former (beginning with the proton and neutron) can never be completely transformed into particles of the second type. This is forbidden by the law of conservation of a specific quantity (the baryon quantum number), which equals zero in the case of mesons, +1 for baryons, and -1 for antibaryons. Because of this law, only baryons and antibaryons can, by mutually annihilating, be converted to mesons (the same is true for resonances).

CHAPTER 3. DIFFRACTIVE AND COHERENT MODES OF PARTICLE PRODUCTION

Diffraction of Particles and Its Unexpected Consequences

As early as 1927, the experiments of Davison and Germer (U.S.A.) showed that by passing electron beams through films of crystalline material one gets exactly the same diffraction phenomenon as in X-ray experiments: on the photographic plate placed behind an obstacle a distinct system of dark and light rings were formed. At that time, the hypothesis of the French physicist, Louis de Broglie, was verified for the first time. This hypothesis states that any material particle having momentum p is at the same time also a wave of wavelength λ, which is related to its momentum by the equation: /47

$$p \cdot \lambda = h.$$

Planck's constant, $h = 6.6 \cdot 10^{-27}$ erg · sec, which was mentioned above, enters into this equation.

Let us consider in greater detail the simplest case of diffraction of a particle-wave on a spherical, completely opaque obstacle of radius R, which can be any other particle which interacts strongly with the first, e.g., a nucleon (Figure 17). In the entire region behind the object, the wave is distorted, and the degree of this distortion depends on the scattering angle θ. Actually, the amplitude of the wave varies in space according to the law $\left|\sin \frac{\Delta L}{\lambda} \pi\right|$. As a result, two waves which "go around" the obstacle on different sides completely cancel each other under the condition:

$$\Delta L = 2\,R \sin\theta = \lambda/2 = h/2p$$

and, conversely, they do not interfere with each other at all when they have the same phase $\Delta L = 0$, i.e., at $\theta = 0$.

To recapitulate, at the center of the image formed by a wave on a photographic plate, there must be a black spot, and the radius of the first light ring is inversely proportional to the momentum of the incident wave-particle and the size of the stationary obstacle-particle, and it is equal to $\theta_1 = h/4Rp$ (in angular degrees). If we insert specific values into this equation, e.g., a pion of energy 10 GeV ($\sim 10^{-2}$ erg) and, consequently with a momentum $\sim$ 10 GeV/c (c is the velocity of light) impinging on a nucleon of radius $r_0 \sim 10^{-13}$ cm must give a dark ring of a width of roughly two angular degrees. /48

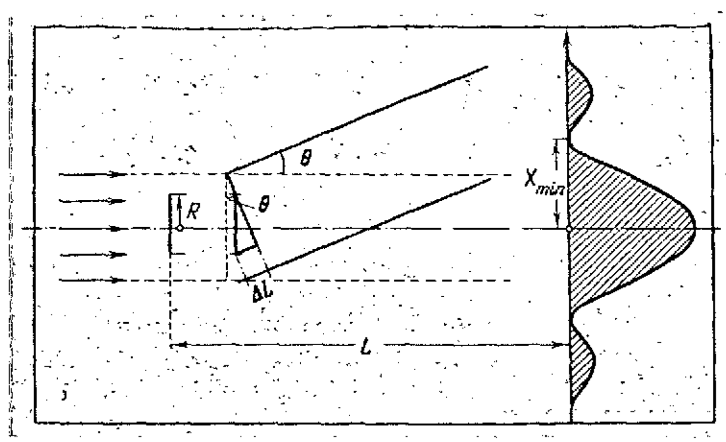

Figure 17. Diffraction of a wave on an opaque obstacle:

Position x_{min} — first minimum in the intensity of the scattered wave according to the relation $\Delta L = 2R \cdot \sin\theta_1 = \lambda/2$ with $x_{min} = L \sin\theta_1$ (λ — wavelength; R — radius of the obstacle; L — distance to the screen)

Returning again to the corpuscular picture of the phenomenon, one can say that here the scattering of the incident particle occurs, and that the probability of scattering decreases with increasing angle. In other words, to the incident particle correspond, in different cases, different transverse momenta $p_\perp = |p \sin\theta|$, whose probability distribution decreases with the scattering angle θ, i.e., with the value of the momentum $p_\perp$ according to a well-defined law.

It is important that the characteristic value of the transverse momentum in strong interactions is equal in order of magnitude to the pion mass multiplied by the velocity of light $(p_\perp \sim mc)$. The commensurability of these quantities is quite natural if one considers the entire process of interaction as an exchange of virtual pions whose "clouds" determine the spatial structure of nuclear particles. As we shall see later, the same order of magnitude of transverse momenta is characteristic of practically any strong interactions (including also inelastic) associated with multiple particle production. /49

Now let us consider how this changes if the incident particle strikes not one nucleon, but a whole nucleus. First of all, it is clear that this is an object of large size. Since nucleons are always "packed" in the nucleus with roughly equal density (this is related, in particular, with the short range interaction force), the total volume of the nucleus is proportional to the atomic number A of the material, and the radius is $\sim \sqrt[3]{A}$. The structure of each nucleon is determined by the emission of virtual pions, and this implies that the size r_0 of each nucleon is related to the pion mass m_π by the relation $r_0 \sim h/m_\pi c$ (again as a consequence of the uncertainty relation).

Thus, in a first approximation, the nucleus is an almost opaque sphere (later we shall see how important this qualifier "almost" is) of radius $R = r_0\sqrt[3]{A}$.

We shall now demand that the conditions of interaction of the incident wave-particle are equal for each nucleon of the nucleus. From the wave point of view, this implies in the first place that the phase relation of the scattered waves must be roughly constant over the entire extent of the nucleus. Then all interacting nucleons of the nucleus will be in phase, or, as is usually said, coherent. This leads to a mutual enhancement of their interactions. But this condition in turn requires that the change in wavelength be small with respect to the dimension R of the nucleus. If we now return to the values of R and r_0 given above and recall the uncertainty relation between the length of a wave and its momentum, then we see that a necessary condition for coherence is the smallness of the longitudinal momentum transmitted to the nucleus in relation to the value of the quantity $m_\pi c/\sqrt[3]{A}$, and not only in relation to its initial value.

The Soviet physicists I. Ya. Pomeranchuk and E. L. Feinberg were the first to note that, in spite of the small value of the transferred momentum, the interaction of particles can be coherent and diffractive and, nevertheless, it can be essentially inelastic "from the point of view" of the incident particle. Hence, the target particle will play the role of not only an opaque, but also /50 stable, obstacle, and the projectile particle will fall apart (dissociate) into separate particles whose total mass exceeds the mass of the incident "projectile".

At first glance, this appears as a completely paradoxical situation. One of the "partners" of the interaction does not even alter its state, except for the relatively small "recoil"; the second, although being an elementary particle, is nevertheless excited and transformed into a significantly heavier (and, consequently, very unstable) system, all without penetrating the target, and almost as if without even touching it.

There is, however, no violation of the principle of causality involved in this phenomenon. The wave characteristics of elementary particles are being expressed in what is occurring here. An opaque obstacle in the case of high energies severely distorts the incident wave. This results in a fundamental change in its characteristics, primarily in the relation between the value of the energy and that of the momentum, in spite of the relatively small change in momentum. In fact, we shall recall the relationship between particle energy E, its momentum p, and mass M:

$$E^2 = p^2c^2 + M^2c^4.$$

From this, it is apparent that at very high (with respect to the quantity Mc) momenta, even a small decrease in momentum results in a significant increase in mass if the energy is held constant. At the same time, a slight decrease in momentum occurs on striking the target, as an unavoidable consequence of the wave nature of elementary particles.

A prediction of the theory later (in 1964 - 1965) received striking confirmation in experiments on the large accelerators. It was found that at energies on the order of 10 GeV, a charged pion incident on a nuclear target can in some, not all too rare, cases "fall apart" at once into usually three charged pions. An incident proton, on the other hand, yields another proton and two, usually charged, pions. Such processes can be observed particularly well in photoemulsions (Figure 18). The track of the incident particle and three tracks of the secondary particles dispersing at small angles (on the order of a few degrees) are clearly visible in it. No other tracks which could indicate an excitation of the target nucleus leave the point of interaction. /51

By an expert glance, a specialist will recognize this event without difficulty in a background of a large number of "normal" processes of multiple particle production, if the energy E_0 of the incident particle is known. In fact, in the center of inertia of the incident proton and one of the target nucleons, the scattering symmetry of the particles must be satisfied relative to the plane perpendicular to the direction of the incident particle. In this system of coordinates in which we observe the given event (the laboratory system) this plane is transformed into a cone with an opening angle equal to $1/\gamma_c$ radians, where the quantity γ_c (the Lorentz* factor of the center of inertia system of the interacting particles) simply expressed in terms of the energy is: /52

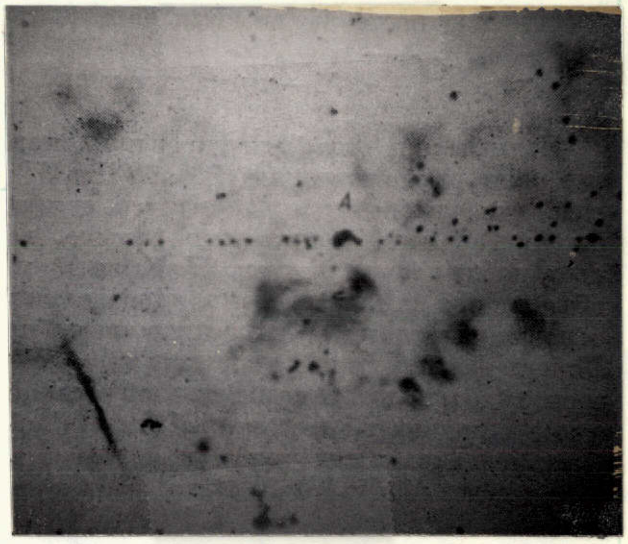

Figure 18. Microphotograph of a typical diffractive process event $\pi + A \rightarrow 3\pi + A$ on nuclei of a photoemulsion at a poin energy of 60 GeV. The track of the primary pion is at the left; the tracks of three secondary particles diverge from point A (data of M. I. Tret'yakova)

$$\gamma_c \approx \sqrt{\frac{E_0}{2M}}$$ (M is the mass of the target).

If the target were one of the nucleons of the nucleus, then using the specific values E_0 = 60 GeV, M = 1 GeV, we would obtain

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*The quantity $\gamma = 1/\sqrt{1-(v/c)^2}$, is called the Lorentz factor, where v is the velocity of the given system (or particle), and c is the velocity of light. The quantity γ is a very important characteristic of a rapidly moving particle because it is equal to the ratio of its total energy to its rest energy.

as the opening angle of the symmetry cone a value of about 10°, i.e., significantly more than the emission angles of all observed particles. The unusual character of this event is explained by the fact that the target (a nuclear photoemulsion) is not related to the center of inertia system of the observed particles. The Lorentz factor of this system, $\gamma' = E_0/M_b \approx 60$, is only slightly less than that of the initial particle (the mass of the excited initial particle is $M_b \approx 1$ GeV). The absence of any traces of nuclear excitation (no slow fragments are emitted from the nucleus) confirms the given "diagnosis".

Subsequently, it will be shown that the phenomenon of diffractive particle production almost completely disappears for energies less than 3 - 5 GeV and, on the other hand, its probability continues to increase with increasing energy, at least up to 200 GeV (such energies became attainable after the unique Soviet accelerator at Serpukhov, and then the accelerator at Batavia, U.S.A., began operating).

Is It Possible to Exchange Parts of the Vacuum?

Let us now recall that in Chapter 2 we discussed the model of elastic scattering of real particles, which depends on the exchange of virtual particles. We will try to relate the diffractive process considered above to the exchange of certain virtual objects possessing a completely determined set of physical characteristics which do not necessarily have to be the same, as in the case of real particles. For the graphic representation of similar processes, Feynman diagrams are used, which were referred to previously (see Figure 11b).

In Figure 19 is shown the Feynman diagram for the process of the conversion of a single negatively charged pion into three pions as a result of diffraction on an atomic nucleus. In this diagram, the intermediate (virtual) particle, which serves as a carrier of momentum, is denoted by the symbol P. This is the /53 pomeron, a particle which was first introduced into the "use" of theoreticians by I. Ya. Pomeranchuk. The pomeron cannot carry any physical quantities except momentum. For this reason, the pomeron can be considered the quantum of the vacuum, because its most important physical characteristics and, above all, its electric charge, are equal to zero, as are those of the vacuum. It is for this reason that in the diffractive process only an odd number of charged particles are formed, since the total electric charge was equal to the charge of the incident particle, i.e., -1. The vacuum pole does not carry a charge. It would seem that a single neutral pion could emerge, but, in fact, neutral pions are created only in pairs. The reason for this is the necessity of conserving still another quantum number G, called parity, which equals -1 for any pion, $(-1)^2 = +1$ for any pair of pions, and, finally, $(-1)^3 = -1$ for three pions. But when there is sufficient energy available, it is possible to create two pairs of pions. All these conditions are met in the formation of a single heavy particle (or more precisely, a resonance), which is called the A_1-meson and has a mass of 1070 MeV. One must not exclude the possibility that, instead of a quickly decaying resonance A_1, a combination of a π^--meson with the neutral ρ-meson, particles just as short-lived as the A_1, are formed.

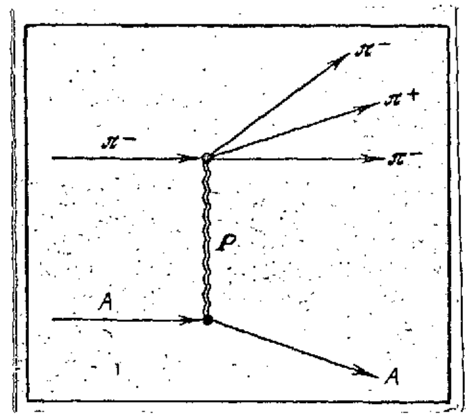

Figure 19. Feynman diagram for the diffractive production of pions on a nucleus. P — pomeron

Ought not the validity of the diagram shown in Figure 19 and the whole ideology associated with it be verified by finding the pomeron in nature in a "pure", free state? Among the diverse /54 "assortment" of processes observed during the last six years of the formation of particles with the decay of free resonances, there appeared, in fact, two candidates having the necessary set of quantum numbers. The first is the neutral f-meson, which has a mass of about 1270 MeV, and decays 80% of the time into two pions and sometimes even into two pairs of pions, or into a K-meson paired with its anti-particle ($\bar{K}$). The second candidate is also a neutral particle, the f'-meson, a heavy "twin" of the f-meson, with a mass of about 1515 MeV, and which decays approximately 70% of the time into a K + $\bar{K}$ pair. The life-time of both particles is about 10^{-23} seconds.

Let the reader not be perplexed by the fact that there is more than one candidate for the post of the quantum part of the vacuum. There can be no "competition" in the struggle among them for this important post. The point is that, in the theory of Regge (which refutes the presence of the corresponding processes of momentum exchange in scattering, including also diffraction), virtual states must necessarily find their natural continuation in the form of resonances (or simply particles) in proportion to their change in angular momentum, and this repeats itself each time as soon as the angular momentum assumes integer values differing one from another by two units of Planck's constant.

In this fashion, instead of competition among the corresponding free states there are, according to the ideology of the "Reggeists", their "recurrences", i.e., a type of periodic regeneration in proportion to the motion of the pole of a given trajectory in angular momentum space, and, related to this, an increase in the square of the mass each time by the same value.

Concerning the Properties of That Which Hardly Exists

The processes of the diffractive creation of particles is not simply a unique curiosity, a paradox even in the world of strongly interacting particles at high energy. For experimental physicists, this phenomenon serves as a unique instrument for the elucidation of several important characteristics of resonances which seem to be elusive because of their short life-times.

We will examine what characterizes processes of diffraction productive of resonances on nuclei of various sizes. First, the emission angles of secondary waves must decrease as the total number of nucleons of the nucleus A, and, consequently, its transverse dimensions, increase. This is a consequence of the basic conditions of particle-wave diffraction. As a result, the curves of the differential cross section σ_{dif}, reflecting the dependence of the cross section of the process on the magnitude of the momentum t transferred to the created resonance (Figure 20a), will "climb" up steeper and steeper with increasing A when t tends to 0. This peculiarity of the differential cross sections is convenient in that it allows one to clearly separate diffractive processes of particle creation occurring on the nucleus as a whole from the same particles produced on individual nucleons of the nucleus. /55

Second, insofar as the process has a coherent character, i.e., the interactions with the individual nucleons of the nucleus occur practically in phase and add, the total amplitude is proportional to the number of nucleons of the nucleus A, and, consequently, for light nuclei the probability of the process is proportional to A^2. For a sufficiently large number of nucleons, the longitudinal dimensions of the nucleus (in the

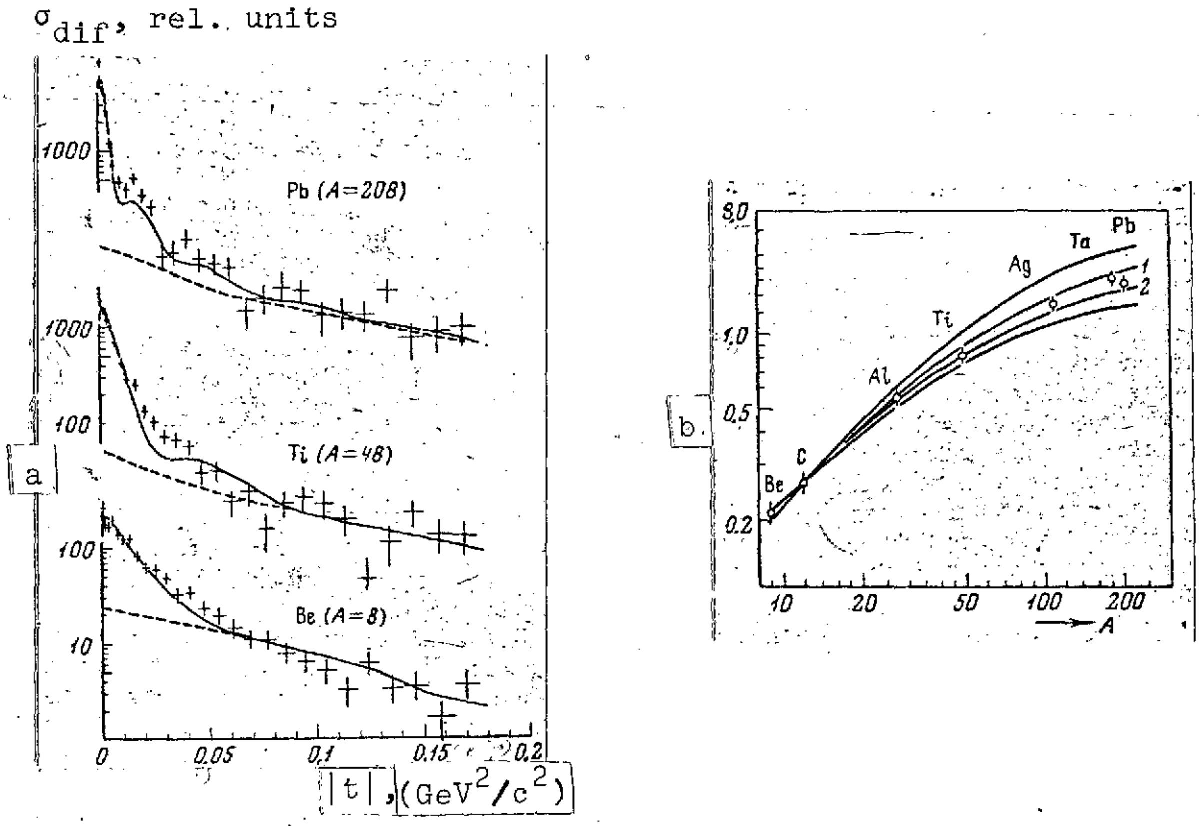

Figure 20. a) Distributions of momentum-squared to various nuclei in the diffractive production of A_1 resonances with pions of energy 15 GeV (experiment of S. Bemporay et al.). The contributions of non-diffractive processes are indicated by the dashed lines; b) the dependence of the relative cross sections of the processes studied on the atomic weights of the nuclei (in the same experiment) and comparison with the calculated cross sections using various σ_b for the interactions of the A_1-resonance with nucleons:

$$1 \text{ — } \sigma_b = 20 \text{ mb}; \; 2 \text{ — } \sigma_b = 25 \text{ mb}$$

direction of the incident particle) increase so much that the probability of absorption of the created resonance in the nuclear matter becomes significant and reduces the initially quadratic increase in the yield of resonances. If this yield of resonances of a given type is plotted as a smooth function of the number of nucleons in the nuclei, then the overall character of this function (Figure 20b) will depend on the value of the cross section

σ_b for the interaction of these resonances with the separate nucleons of the nuclei. By studying the experimental dependence of the resonance yield on the number of nucleons in the nucleus and comparing the results with theoretical calculations for different cross sections σ_b, the actual value of the cross section σ_b can be determined.

At a physics conference in January, 1968, at CERN, the experimental results of a large collaboration of scientists at the electron accelerator DESY in Hamburg were reported. They studied the coherent production of three resonances (ρ, ϕ, ω) belonging to the same family of vector mesons on a very wide range of different nuclei, from beryllium to lead. Those involved in this experiment were able to determine the values of the cross sections for nuclear absorption, and proved for at least two reson- /57
ances (ρ and ω) that they were in good agreement with the theoretical predictions.

It is necessary to mention one circumstance which will be discussed in detail in Chapter 7. There exists a theory of strongly interacting particles (hadrons) based on the existence of several symmetries (broken only by the weaker interactions) of fundamental physical properties of matter. These particles can be incorporated into a closed group, a family. By knowing the specific characteristics, in particular, the interaction cross sections of the more "long-lived" members of this family, one can make quantitative predictions of the cross sections of the other, more "ephemeral" members of the family of resonance-particles. In more difficult cases (e.g., the family of spin 1 mesons, which includes the ρ, ω, and ϕ mesons) when there are no long-lived members of the family, it is possible to make theoretical calculations of approximate cross section values and, by comparing them with experimental values, verify the initial theoretical concept.

In this manner, and in spite of the fact that life-times of the resonances are comparable to their formation times and the characteristic interaction times of strong interaction in general, physicists have contrived to find reliable witnesses of their existence. These witnesses turned out to be nucleons of the same nuclei on which the resonances were produced. Since the whole nucleus holds together just because of the strong interactions of its constituent nucleons, the distance between neighboring nucleons is sufficiently small that any particle moving close to the velocity of light can overcome it in the time interval required for the realization of one elementary act of the strong interactions. The possibility of observing a resonance is made still easier in proportion to the increase in its production energy on a nucleus, since for any rapidly moving object all time scales are lengthened according to the theory of relativity. This relativistic effect is also reflected in particle life-times since these times are increased by as many times as a moving particle's total energy is greater than its rest energy.

We are now convinced that resonances can exist not only in /60
a virtual form (as a carrier of the interaction between particles), but also in a free one as a "product" of the excitation of an "elementary" particle in a diffraction process. Let us return to the question posed in the previous chapter: what is a resonance?

The very name "resonance" reflects the historically-formed conceptions of these unusual objects as being made up of two or more particles in a relatively steady state of resonance interaction. However, it gradually became evident that resonances possess all the same characteristics of "normal" particles which were formerly considered elementary. In particular, the length of their life-times do not so cardinally exceed the limits of longevity of real particles (let us say, the π^0-meson), and the spatial "extent" (characterized by the absorption cross section in nuclear matter) does not differ at all from the dimensions of elementary particles.

Besides, the "former" elementary particles, e.g., the mesons or baryons, can be transformed into the corresponding meson (integral spin) or baryon (half-integral spin) type. This indicates that, first, "elementary" particles possess a no less complex structure than a resonance and, second, the differences between various families of particles and resonances can be significantly greater than those between particles and resonances united according to a series of essential physical characteristics (among which mass is not included) in one and the same family. Recently it has been customary to set the border between "stable" (to decay due to strong interactions) particles and resonances at a life-time of $\sim 10^{-22}$ seconds. Below this limit of "longevity", the uncertainty in mass, which is related to rapid decay, already becomes equal to the average value of the mass itself.

From among the large number of particle-resonances currently known (more than 100, not counting anti-particles), 24 of the more abundant ones are given in Table 1, together with their characteristics.

More precisely, in the Table are represented 11 charged multiplets, i.e., small groups of "kindred" particles, differing from one another only in charge (in the same way as the π^+, π^0, and π^- mesons, or the proton and neutron). As follows from the first column of the Table, the closest "candidate" for a stable particle is the η-meson, which is not so different in its physical characteristics from the π-meson, inasmuch as the π^+-meson /61

TABLE 1. THE MORE ABUNDANT RESONANCES*

Symbol	Charge state	Spin, $\hbar$	Mass, MeV	Life-time, sec	Characteristic production reactions	Maximum cross section σ_m (mb) and energy of incident particle E_0 (GeV)	Fundamental decay mode	Probability of corresponding decay, %	Remarks
A. Meson resonances									
η	0	0	540	$2{,}5 \cdot 10^{-19}$	$\pi^- p \to \eta n$	~ 3 $(E_0 \sim 1)$	$\to 2\gamma$ $\to 3\pi^0$ $\to \pi^+\pi^-\pi^0$	38 30 24	More frequently treated as stable particles
ρ	+, 0, −	1	765	$1{,}3 \cdot 10^{-24}$	$\pi^- p \to \rho^- p$ $\pi^- p \to \rho^0 n$	2—3 $(E_0 \sim 3)$	$\to 2\pi$	$\simeq 100$	
ω	0	1	784	$1{,}7 \cdot 10^{-23}$	$\pi^+ n \to \omega p$	~ 2 $(E_0 = 1{-}2)$	$\to \pi^+\pi^-\pi^0$ $\to \pi^0\gamma$	$\simeq 90$ ~ 9	
K^*	+, 0	1	892	$3{,}5 \cdot 10^{-24}$	$K^+ p \to K^{*+} p$ $K^- p \to K^{*0} n$	~ 2 $(E_0 \sim 2)$	$\to K\pi$	100	
A_1	+, 0, −	1	1070	?	$\pi^- p \to A_1^- p$	$\sim 0{,}5$ $(E_0 \sim 4)$	$\to \rho\pi$	100	Possible combin. of ρ- and π-mesons
f	0	2	1270	$1{,}1 \cdot 10^{-24}$	$\pi^+ p \to f \pi^+ p$	$\sim 0{,}3$ $(E \sim 5)$	$\to 2\pi$	$\simeq 80$	
A_2	+, 0, −	2	1310	$1{,}7 \cdot 10^{-24}$	$\pi^- p \to A_2^- p$		$\to \rho\pi$ $\to \eta\pi$	77 16	Fundamental resonance in πp reactions for $E_0 > 10$ GeV

(Table continued on following page)

TABLE 1. (continued)

Symbol	Charge state	Spin, $\hbar$	Mass, MeV	Life-time, sec	Characteristic production reactions	Maximum cross section σ_m (mb) and energy of incident particle E_0 (GeV)	Fundamental decay mode	Probability of corresponding decay, %	Remarks
B. Baryon resonances (isobars)									
Δ	+2, +1, 0, −1	$3/2$	1230—1236*	$1,5 \cdot 10^{-24}$	$pp \rightarrow \Delta^{++} n$	~ 10 ($E_0 \sim 3$)	$\rightarrow N\pi$	99,5	Mean value of the mass obtained in various reactions is indicated in given range
N' (1440)	+, 0	$1/2$	1435—1505*	10^{-24}	$\pi^- p \rightarrow N' + \pi^-$	$\sim 0,7$ ($E_0 = 10$—30)	$\rightarrow N\pi$ $\rightarrow N2\pi$	60 40	
N' (1520)	+, 0	$3/2$	1510—1540*	$1,5 \cdot 10^{-24}$	$pp \rightarrow N' + p$	$\sim 0,4$ ($E_0 = 10$—30)	$\rightarrow N\pi$ $\rightarrow N\pi$	50 50	
N' (1690)	+, 0	$5/2$	1680—1692*	$1,5 \cdot 10^{-24}$	$\pi^+ p \rightarrow N' + \pi^+$	$\sim 0,8$ ($E_0 = 10$—30)	$\rightarrow N\pi$ $\rightarrow N2\pi$	60 40	

*Commas in numbers represent decimal points.

has a life-time of $\sim 10^{-8}$ seconds, and the π^0-meson $\sim 10^{-16}$ seconds.

One of the basic criteria of abundance is the relative probability of forming a resonance in the interaction of two strongly interacting particles, pions, kaons or protons with protons.

It has been convenient to include several comments in Table 1.

First, it is indicated that all meson resonances have integral spin (in units of Planck's constant $\hbar$ divided by 2π), and all baryon resonances — half-integral spin. As will be discussed in detail in Chapter 7, this can be explained by the fact that the former consist of an even, and the latter of an odd number of the same "subparticles", each with spin $\hbar/2$.

Second, the meson resonances, as a rule, are lighter than the baryon resonances, and they are not as different among themselves as are the pion and proton.

Third, the life-times of almost all resonances are too short and, consequently, their mass uncertainties (in accordance with the laws of quantum mechanics) become comparable to the masses themselves.

Finally, the probability of forming the majority of resonances decreases, in general, with increasing energy of the particle which produces them. The last three baryon resonances, however, are produced quite effectively at energies in the tens of GeV. This is related to the fact that by nature they are related to the nucleons (therefore, they are denoted by the same symbol N as are the nucleons), and their production proceeds via the diffractive process by means of pomeron exchange. This saves them from dying out with increasing energies of the colliding particles.

CHAPTER 4. PERIPHERAL PROCESSES

"Memory", Inertia, and the Structure of Particles

Let us return to the processes of formation of secondary /62 cosmic radiation in the Earth's atmosphere. As was mentioned in the introduction, physicists at the beginning of the 50's already knew that, as a result of strong interactions with the nuclei of atoms of the air, the primary particles, the protons, gave rise to all three components of the secondary radiation. In each of these interactions, charged pions (π^+ and π^- could be produced, giving rise to (as a result of decay) the penetrating or hard muon component. In such processes, through the formation of π^o-mesons, the first step in the development of the quickly absorbed electron component (soft component) was realized. And finally, the products of the same interactions which do not decay in the air, the nucleons, comprise the nuclear-active component, which is capable of splitting more and more atomic nuclei into their constituent parts while not losing any energy at all.

In order to understand the processes occurring, it was necessary to progress from a qualitative analysis of the phenomena to a quantitative one and, above all, measure the energy relationships. One of the possible energy analyses was carried out by N. L. Grigorov and his colleagues at MSU with the aid of electronic apparatus (counters, ionization chambers) carried to the upper levels of the atmosphere by a not very large balloon. By making the measurements under various thicknesses of lead, they were able to determine the energy flux of the electron-photon component at each level observed. Tracking the response of the instruments at all altitudes, the scientists measured the total energy deposited by all π°-mesons. Finally, having carried out the parallel measurements at two latitudes (31° and 55° North latitude), and knowing the critical energy necessary for the protons to overcome the repulsive geomagnetic "barrier" at each /63 of these latitudes, the experimenters were able to estimate the mean energy of the incident protons.

The subsequent mathematical analysis of the data together with fully plausible assumption (in particular, that the π^+, π^-, π°- mesons are equivalent) resulted in two very important facts. First, at energies of 3 and 20 GeV, each nucleon loses on the average no more than 30% of its energy in producing pions in strong interactions with light nuclei. Second, a large part of the remaining 70% of the energy is carried off, as a rule, by only one secondary nucleon (either a proton or a neutron). It is true that later studies showed that not all of the initial premises were true. In particular, it was necessary to reconsider the data of medium range nucleons before interacting with the nuclei. Nevertheless, the basic qualitative result, the sharp separation of the nucleon from all the remaining secondary particles in both energy and direction, remained unchanged.

These results were verified by means of a more graphic method in experiments of other Soviet physicists at the P. N. Lebedev Institute. They used a cloud chamber in conjunction with a magnetic field. The energy of the incident nucleon was measured in an ionization calorimeter, and the energies (or rather the momenta p) of the secondary charged particles (these were principally pions) were determined from the curvatures of their tracks in the magnetic field, using the simple relation:

$$pc = 300\ H\rho$$

(c is the velocity of light, H is the magnetic field in Gauss, ρ is the radius of curvature of the track in centimeters, and pc is the momentum in eV). In investigations with the cloud chamber, it was observed that multiple pion production is accompanied by the emission from the nucleus of a slow proton, having at most several hundred MeV (i.e., on the order of 1% of the energy of the primary particle). It was completely logical to consider this slow particle as the secondary partner of a strong interaction which underwent a relatively small (compared to the energy and momentum received) recoil. In order to understand the characteristics of the interaction process, it is important to deal with characteristics of motion which do not depend on the choice /64
of a coordinate system. The simplest of these characteristics is the projection of the momentum on the plane perpendicular to the direction of motion of the incident particle. It is usually denoted by the symbol $p_\perp$ and maintains its value in any system of coordinates moving in the direction of the incident particle, i.e., as the physicists say, it is a transformational invariant.

The projection of the momentum on the direction of motion of the incident particle ($p_\parallel$) or the reduced longitudinal momentum of the secondary particles are not suitable as invariant characteristics of their motion, and neither is the change in energy ΔE or momentum Δp of any specific particle due to its interaction with other particles — for example, in elastic scattering. However, the simple combination of two quantities expressing momentum and energy loss in the interaction, namely, the quantity

$$t = (\Delta pc)^2 - (\Delta E)^2$$

(where c is the velocity of light) is an invariant. Indeed, t is the same invariant quadratic quantity which we introduced in discussing Regge theory. It is a good measure of the transfer of momentum.

For a particle of mass M, which is stationary prior to the collision (the target), a simple relation results:

$$-t = 2ME_{kin}$$

i.e., the recoil kinetic energy (E_{kin}) is also a possible measure of the invariant momentum transfer. What are the main results obtained in meson production experiments by means of inelastic collisions of two nucleons (in targets above the cloud chamber)? It was found, as Grigorov suggested, that each of the nucleons experiences, as a rule, a small (compared to the incident energy) loss of momentum and, as a result, is energetically distinct (or is, as is often said, a "leading" particle) among all the secondary particles. In other words, it is as if the secondary particle "remembers" the nature of the primary particle by approximately conserving its energy and direction of motion. This may /65
be considered a result of each nucleon colliding with a small "piece", a structural element of the other nucleon. As far as we know from the foregoing, the nucleon can be represented as several cores, each surrounded by a meson "atmosphere". As a result, usually only the "periphery" of the nucleon participates in the reaction. In this way, the physicists' concept of the peripheral nature of the interaction originated for both elastic scattering and multiple particle production.

It is interesting to note that the more the "inertia" of the primary particle is expressed, the fewer are the new particles (pions) that are produced. Approximately the same thing is observed in collisions of pions with nucleons, except that the "leading" particles turn out to be two or three pions and that, in the case of a small number of produced particles, they seem to disperse asymmetrically (in the c.m. system of the pion and proton, the majority of the particles leave in the direction of the incident pion). The last fact can be interpreted as a consequence of the meson having an "atmosphere" consisting of heavier virtual particles than that of the nucleon-antinucleon pair. Other interpretations are not lacking (we shall consider one in detail in the last chapter). It may be that the number of structural elements of the pion are fewer than those of the nucleon. Even if the absolute masses of these structural elements, which act as the actual "projectiles" and targets of colliding particles, are equal, their relative masses may be different for the pion and the proton.

How Can One Get an Inelastic Interaction From "One-Half" of an Elastic Interaction?

The peripheral character of the process of pion production is best expressed and most easily described when the pion number is small. We will consider the simplest model which describes the phenomenon with the help of symbolical diagrams of the process which are similar to Feynman diagrams. Let only one pion be produced in a collision of two protons. One of the possible peripheral processes which occurs in this case is shown in Figure 21. In this picture, one of the protons emits a virtual pion at the point 0 (at the bottom of the diagram), and then the other proton absorbs it, forming an excited "subsystem" of mass M (cross-hatched in the diagram). One can assume that the new pion is produced simply by elastic scattering of the virtual pion by the proton p_1, and the proton p_2 experiences charge exchange, being transformed into a neutron. In the mathematical

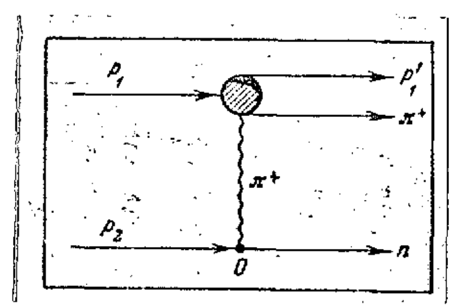

Figure 21. One of the variations of single pion exchange in a single pion production reaction in p-p-interactions

description of the processes with which is associated virtual particle emission (not necessarily pions), one of the main factors is the calculation of the quantity called the propagator function. This function is related to the probability of a virtual particle of mass μ and the square of the momentum transferred by its help $-t$ (recall that the square of the momentum transferred is denoted by t with a minus sign). The propagator function has a quite simple form:

$$F(t)=\frac{1}{(t-\mu^2c^2)^2}=\frac{1}{(|t|+\mu^2c^2)^2}.$$

Its chief characteristic is the pronounced dominance of small (relative to the quantity μc) momentum transfers. This is related to the virtual nature of the principal "character". In particular, if the virtual particle is a pion, for which $\mu^2c^2 \approx 0.02\ GeV^2/c^2$, then the probability of recoil of the nucleons between which it is exchanged decreases by a factor of 50 in going from $t = 0$ to $t = 1\ GeV^2/c^2$ (as follows from the formulas introduced earlier, the kinetic energy of the nucleon reaches 0.5 GeV in this process).

The decisive role of the propagator in determining the basic characteristics of phenomena is quite evident in the case of quasi-two particle reactions (Figure 22a), in which one or both of the colliding particles cannot only undergo recoil but also /67
resonance excitation to a state characterized by new quantum numbers. In Figure 22b is shown the experimental distribution of momentum transfer and the propagator function for comparison.

At low colliding proton energies (1.5 - 3 GeV), pion production occurs chiefly by means of an intermediate state in which a resonance of mass 1236 MeV is formed. This is the lightest baryon resonance (isobar), and the high probability of its

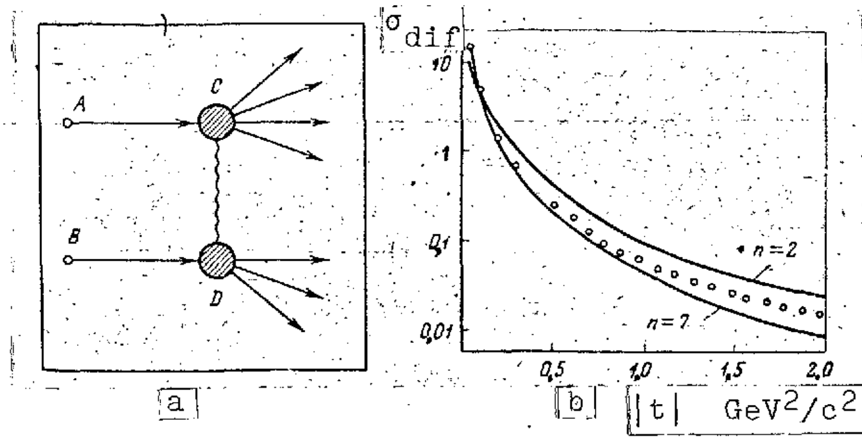

Figure 22. a) General scheme of the quasi-two particle process of multiple production; b) distribution of momentum transfer $|t|$ in the reaction $\pi^- p \to p + n\pi$ at an energy of 16 GeV. The circles indicate the values of the propagator function $1/(t - \mu^2 c^2)^2$

production corresponds to the sharp peak in the elastic scattering cross section of free π^+-mesons on protons (see Figure 14b). One of the features of this process is the large (five-fold) preponderance of π^+-meson production over π^0 production.

At higher proton energies (higher than 10 GeV), the formation of heavier isobars (as intermediate excited systems) with masses 1440, 1520, and 1690 MeV begin to play a larger and larger role. On decaying, each of these isobars can emit one or two pions with roughly equal probability. They do not differ in their quantum numbers from nucleons and, hence, can be produced by diffractive means, i.e., by exchanging a pomeron between the nucleons. /68
The probability of such an exchange relative to a single pion exchange at first increases, and then practically does not decrease with increasing energy of the colliding nucleons (whereas with pion exchange this probability decreases in inverse proportion to the square of the energy after reaching a maximum).

Processes of few pion production in collisions of pions with protons are, as a rule, difficult to explain in terms of the simple peripheral model of single pion exchange. In any event, it is often necessary to consider two or even three possible exchange processes: ρ-meson (with mass 765 MeV, ω-meson (with mass 785 MeV), or A_2-meson (with mass 1310 MeV). Only elastic "charge exchange" reactions — the transformation of π^--mesons into π^o-mesons — comprise a "pleasant" exception. In such reactions, only ρ-exchange is "allowed". Therefore, the reaction:

$$\pi^- p \rightarrow \pi^0 n$$

has recently been studied with interest, and gives reasonable confirmation of the basic laws of Regge theory under the clearest conditions over a large energy range of the colliding particles.

Let us return once again to the diagram of the type given in Figure 21. It is obvious that, on account of the symmetry of the initial state, proton 1 (the "projectile") and proton 2 (the "target") can change roles. Each can be transformed to an excited system. When this system decays, 1 - 2 pions are emitted in addition to the baryon, and these pions generally leave close to the direction of the incident proton. In this regard, it is necessary to consider the fact that the target proton, which moves backwards in the center-of-mass (c.m.) system of coordinates of the two particles, also moves forward, but at a large angle, after the transformation to the laboratory (lab) system. The much faster meson can sometimes leave at an angle greater than 90°, even in the lab system. By glancing at the table of resonances with their decay modes, we can convince ourselves that the quasi-two body process allows no more than 4 - 6 free particles (including neutrals) in the final state.

However, in spite of the scantiness of its "repertoire", the quasi-two body reaction and those reducible to it constitute the richest "educational field" for experimenters, since they are /69 used to obtain exhaustive information about the characteristics of any virtual particle.

Perhaps the reactions which have been studied in greatest detail are all of the type $NN \to N\Delta$ (with the participation of nucleons and the production of the Δ resonance), and also $\pi N \to \rho N$, $\pi N \to fN$, $\pi N \to \rho\Delta$ and $\pi N \to f\Delta$ (with the participation of a pion and a nucleon). All these reactions are well described by a single law of interaction of the virtual pion with free (real) nucleons and pions.

The reaction $pN \to NNK\bar{K}$ is also very interesting. It allows one to discover the laws of exchange of the "almost" free K-meson in the process of production of free K and anti-K particles ($\bar{K}$).

The just-as-simple reactions $\pi^- p \to \pi^0 n$, $\pi^- p \to \eta^0 n$ and $\pi^- p \to \rho^- p$ allow the determination of the behavior of the ρ, A_2 and Δ resonances as virtual particles. Finally, a particular case is the study of the momentum distribution of protons in the vicinity of the upper limit of possible energies in reactions which are conventionally represented as

$$p + p \to p + X,$$

in which the system X represents all the created particles except /70 a single, fast proton. Theory indicates that such a reaction gives valuable information about the interaction cross section of the pomeron P with the proton.

On the whole, the basic idea of the existence of some 2-step process related to the initial excitation and subsequent independent decay of the colliding particles has turned out to be very fruitful. As early as 1949, G. T. Zatsepin (USSR) and, in 1952, S. Takagi (Japan) proposed to explain the basic features of secondary cosmic ray formation by means of the phenomenon of the excitation of colliding nucleons at high energy. The renowned Chinese theoretician and Nobel Laureate, C. Yang, who works in the United States, introduced a model of asymptotic fragmentation at the International Conference in Kiev in 1970. His model, which is completely independent of the results obtained with cosmic rays, was based only on accelerator data. At this time, it was asserted that many essential features of multiple production (in particular, the approximate constancy of the cross section of the process and the similarities of the energy spectra as the energy is increased indefinitely) can be considered as simple consequences of the analogous model of excitation and decay (fragmentation) of colliding particles if one does not limit oneself by demanding that the process have a resonance character (with the formation of isobars in the intermediate state of the process).

Finally, in 1972, several physicists tried to find evidence from experiments using intersecting beams of equivalent energy $\sim 10^{12}$ eV to substantiate the "Nova" model, which is based on the assumption of diffractive particle production (discussed in Chapter 3) be means of exciting each of the colliding particles. Since in all these models, the excitation of nucleons was not /71 limited by the production of the already known resonances, the possibility of obtaining an arbitrarily high mass was postulated, assuming in principle an arbitrary large number of produced particles.

As experiments moved to higher and higher regions of energy, it became more and more difficult for the theoretical physicists working on the development of 1-particle exchange models to make ends meet. One of the main difficulties consisted of trying to explain how the particle interaction cross section maintained itself as energy increased. As Regge theory demonstrates, this cross section is unambiguously related and simply proportional to the zero degree elastic scattering amplitude.

One attempt to overcome this difficulty consisted of improving the theory by replacing simple one particle exchange with a multiple peripheral process, which is schematically represented in Figure 23a,b in several of its variations. It is characterized by the consideration of the possibility of multistage emission of virtual mesons (in particular, π-mesons) and their mutual interactions. This, in itself, seems to be a natural extension of the simplest peripheral model. It would appear that virtual particles can behave like free ones, and that their potentialities are immeasurably greater as a consequence of the non-constant value of their mass and the absence of the need to "consider" them in terms of the law of energy conservation in the intermediate state. One of the possible tests of the theory is the verification of the possibility predicated by it of calculating the probability of an elastic process as sums of products of the probabilities of all possible

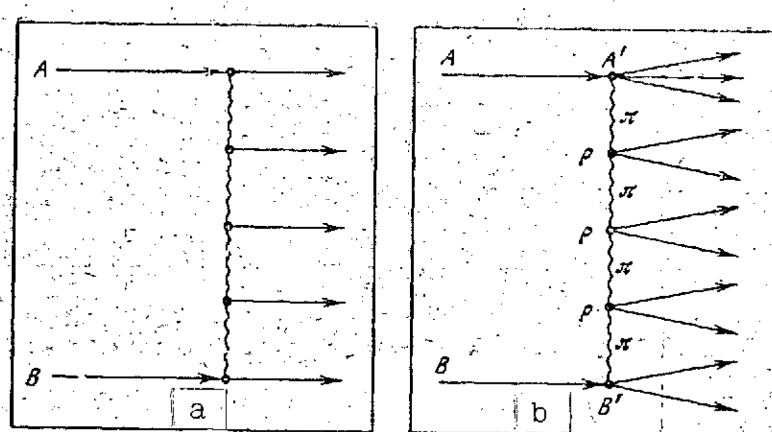

Figure 23. Two possible variations of the multiperipheral process:

a — general form of the diagram of the multiperipheral process; b — one of the variations of the process of virtual π-meson exchange and the creation of particles via the ρ-resonance

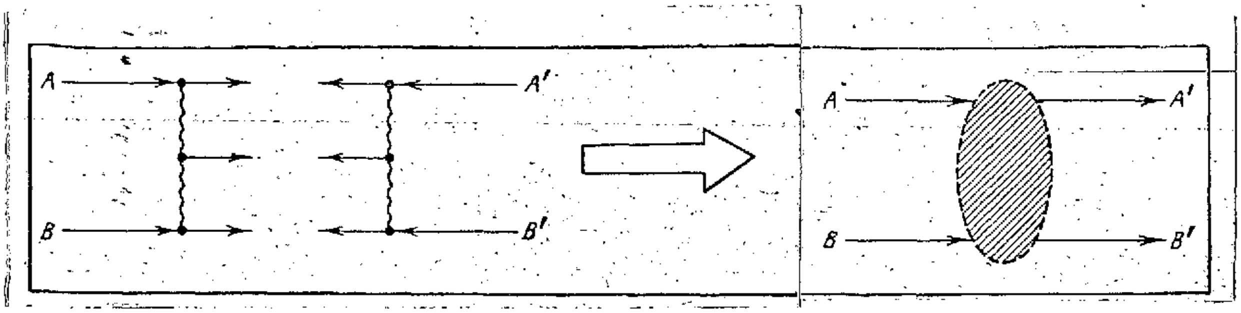

Figure 24. Representation of elastic scattering as two successive processes (forward and backward) of multiperipheral multiple particle production

forward and backward processes of multiple production (see Figure 24). And here, it was found that in taking into account all the /72 conservation laws of physical quantities in the final state, one can in no way succeed in enlisting a sufficient number of possibilities of multiple particle production in order to ensure the necessary probability of return to the initial state, i.e., of elastic scattering of the colliding particles at an angle of zero degrees. An attempt to put together anew a speculatively analyzed mechanism of intermediate interactions of particles met with failure because of a deficiency of "small screws" and construction "parts" (an unskilled watchmaker is, as a rule, confronted with the opposite situation — an excess of parts). The more successful possibility, discovered later, of a complete "assembly" of the elastic interaction from all inelastic ones consisted of the "permission" to use sufficiently heavy "parts" by which the entire "ladder" of the mechanism holds together. This is symbolically represented in Figure 23b. We will return to this question in Chapter 6.

In spite of the many calculational difficulties and the uncertainty of choice among different variants, the multiperipheral model has attained great popularity among physicists and, especially, theorists during the last few years. The reasons for this success can be pointed out.

First, it was found that the simplest types of peripheral processes related to a single step exchange of virtual pions (such reactions, in particular, as $\pi^+p \rightarrow \Delta^{++} \rho^0$ and $\pi^+p \rightarrow \Delta^{++} \omega$ for incident π^+-meson momenta of 3.7 GeV/c) could be studied in detail in experiments. These experiments are characterized by the non-uniform (anisotropic) distribution of the azimuthal angles of the produced particles. If the virtual pion, like a real one, possessed no intrinsic angular momentum (spin), then there would be no reason for the appearance of an anisotropy in the distribution of azimuthal angles. From this, the conclusion unavoidably follows that the spin of the virtual pion (and, in general, any virtual particle) differs from the spin of the corresponding real particle, and, in accordance with the basic hypothesis of Regge theory, it changes with the change in mass of the particle and the momentum transferred by it. This important fact gives rise to the use of "Reggeized" virtual particles in peripheral models.

Second, it became evident that the fraction of particles created through the intermediate state of resonance formation and decay is, generally speaking, quite large and does not change strongly with increasing multiplicity of the process. Thus, for example, the total fraction of pions produced by protons interacting with them by means of the formation of the five more "popular" resonances ρ, f, ω, η, and Δ^{++} typically decreases by a factor of two (from 50 to 25%) when the total number of pions increases from three to five. In addition, this fraction depends weakly on the initial energy of the colliding particles (Figure 25). Therefore, it is "tempting" to consider that resonance production proceeds via a resonance interaction between the colliding virtual particles in a multiperipheral chain of the type shown in Figure 23b. /73

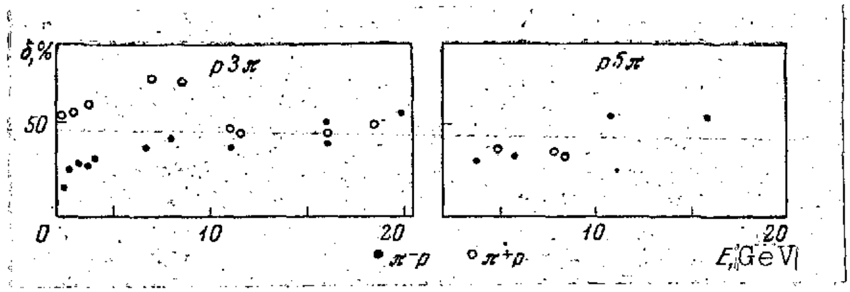

Figure 25. The fraction of pions δ, created via intermediate state resonances in π^-p (•) and π^+p (o) interactions at various energies in the reactions $\pi p \to 3\pi p$ and $\pi p \to 5\pi p$

Complex Regge Trajectories, Successes and Difficulties of the Multiperipheral Model

Let us note once again the two fundamental features of strong interactions at high energies. First, the existence of a very intimate link between elastic scattering and multiple particle production. Second, the relatively large fraction of the energy kept (on the average) by one particle (in the lay system of coordinates). This is characteristic of multiple particle production.

For studying processes, it is very useful to construct a model by whose help one can rigorously deduce the basic features of the elastic and inelastic processes. Such models have been proposed more than once. Perhaps the most popular and thoroughly developed one is the model based on the concept of virtual particle exchange and treated mathematically according to the basic idea of Regge by using amplitudes as analytical functions of complex angular momentum. /74

The first touchstone of Regge theory was the explanation of the energy dependence of the total cross section (elastic and inelastic) for the strong interactions of fundamental particles (nucleons, pions and K-mesons) and their anti-particles with protons and neutrons. In Figure 26, a summary of the current experimental data together with theoretical curves is shown. As is evident, the theory agrees very well with experiment, at least up to an energy of 60 GeV, i.e., the limit attained with the aid of the Soviet accelerator at Serpukhov.

As the energy is increased, the cross section for anti-particles and their corresponding particles gradually converge (more slowly for pions). The cross sections should merge at an energy on the order of 10^{12} eV. The Soviet physicist Pomeranchuk theoretically predicted this gradual (asymptotic) convergence of the cross sections with unlimited increase in energy. /75

In this same asymptotic region, a completely well-defined relation between the proton, pion, and kaon (K-meson) cross sections should exist. At energies attained so far, this was only true to a rough approximation.

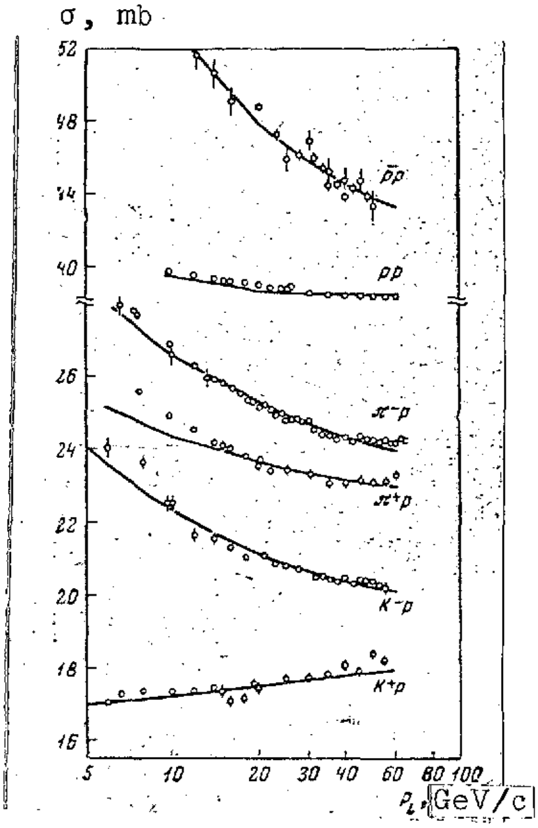

Figure 26. Experimental data for energy dependence of the total cross sections for particle-anti-particle interactions (protons, pions, and kaons) with protons and the results of Regge-model calculations (heavy curves)

It was successfully explained theoretically not only why cross sections decrease with increasing energy, but also why they subsequently increase (as occurred earlier in several instances, such as with K^+-mesons, and later with others).

It is necessary to stress that the agreement of theory with experiment cost a great deal of effort. First, it was necessary to consider the feasibility of exchanging virtual particles of five types, each one corresponding to its own Regge trajectory, i.e., its own law for changing the position of the pole of the interaction amplitude for a change in the momentum transfer t. What one is concerned with here are the trajectories ρ, ω, A, P, and P', where the last two correspond to vacuum poles, which only carry quantum numbers of value zero and, consequently, can participate in processes of the diffractive type which do not "die out" with increasing energies. The total number of free parameters which theorists have at their disposal to "fit" the energy dependence of the cross sections to experiment is in excess of 30!

Second, it was necessary to consider the fact that with the approach to higher energies, the role of particular amplitudes which are more complex than the pole would become more important.

Without getting into the maze of the theory of analytic functions of a complex variable, one can intuitively explain this situation as an unavoidable exchange of pairs of virtual particles or as a process of rescattered hadrons. The very possibility and necessity of rescattering is a result of the strong character of the interaction. In fact, a "strong interaction" denotes an interaction by means of virtual particles, the probability of emission of which is close to unity, in contrast to the electromagnetic interaction for which the probability expression appears with an additional factor of 1/137. Hence, in the absence of an energy limit, the probability of repeated exchange of virtual particles becomes quite high. With the example of
total cross sections, we encounter the situation characteristic /76
of all problems with which Regge theory is concerned. One would expect that, in the region in which the energy tends asymptotically to infinity, all the formulas and relations of this theory

would become quite simple. Unfortunately, the theory does not possess definite criteria for answering the question at what energy this "idyll" will be attained. Besides, by comparing the rate of convergence of the total cross sections of $\bar{p}p$ and pp interactions, on the one hand, and π^-p and π^+p, on the other, one can assume that the boundary of the asymptotic region can be different for different processes. This is related to the fact that the contribution, introduced by the exchange of different virtual particles is different.

In 1973, the question of the asymptotic behavior of the cross section appeared in a completely new way when data concerning proton-proton collisions at energies from 200 - 1500 GeV (these data were obtained on the accelerators at Batavia and CERN) were published. It was found that after passing through a mildly sloping minimum, the cross section started to increase, slowly, but unambiguously. It is interesting that long before this, N. L. Grigorov and colleagues observed an analogous increase (roughly 15%) in the cross section of carbon nuclei in experiments with cosmic rays, but at the time they did not attach any significance to this.

The next touchstone of the theory is the problem of the leading particles, i.e., the energetically isolated particles emitted in the process of multiple particle production. The multiperipheral model (abbreviated MPM) attained the greatest success in describing this characteristic phenomenon. An international association of theoreticians (the Chinese scientist Chan, the Polish scientist J. Loskiewicz, and the American scientist V. Allison) was the first in 1967 to work out and check this model in detail, and good agreement with experiment was obtained. Their model received the "code" name CIA, obtained from the first letters of their last names.

Well, of what did the basic methods and main results of this model consist?

The starting point of the model is the multiplicity of production, the number of particles N created, and after this each "rung" of the ladder diagram (Figure 23a) was considered separately.

The mathematical formulation of the model consists of repre- /77
senting the amplitude of the process as a whole as a product of amplitudes, each relating to one section of the "ladder". At first glance, it appears as if there are too many degrees of freedom even for a given number of created particles, and the arbitrariness of the authors of the model is practically unrestricted. However, the physical idea of this formalism shows through quite clearly if one considers two limiting cases — very high and sufficiently small values of the energy of each pair of interacting virtual particles. The first case, when the energy significantly exceeds 1 GeV, occurs either for very high energy collisions of real particles (hadrons), or for a small number of "steps" of the ladder diagram (see Figure 23a), i.e., for a small number of created particles. In such a case, the basic formula of the model (because of its complexity, we will not write it down here) reduces to the situation in which both of the initial hadrons are energetically isolated after the interaction from all the produced particles.

The second limiting case occurs when the energy of the colliding particles (in the c.m. system) is divided by the number of created particles, thereby decreasing to roughly 0.5 GeV. In this case, all the produced particles have equal rights, and their angular and momentum distributions are governed by a random combinatorial analysis allowing for the conservation of total energy and total momentum. This model predicts (in agreement with experiment) that with further increase in the number of created particles, the probability of the whole process quickly falls when the average energy of each particle becomes less than 0.5 GeV.

In the final analysis, all models based on the experimental fact that, with a decrease in the number of secondary particles N or with an increase of the incident energy, the consequent increase of energy of each pair of created particles must result in a smooth transition from the complete "mixing" of all produced particles to a sharp separation of two leading particles. By choosing the parameters (this is done with the aid of a computer) a reasonable agreement with experiment was attained for the longitudinal momentum distributions of the different types of particles (π^+, π^-, π^0 and p (in p-interactions at energies of 8 and 16 GeV).

The broken lines in Figure 27 are constructed on the basis of an enormous amount of experimental data (many thousands of measurements in the bubble chamber) obtained by the Krākow group of Chizhevskiy. The theoretically calculated smooth lines agree very well with experiment. /78

The CLA model predicts a constant value, independent of the multiplicity for the mean transverse momentum of the particles for both protons and pions. This value is close to 0.4 GeV/c. We will subsequently see that this is really a fundamental characteristic of multiple particle production, but the interpretation in various models appears completely different.

Returning again to the longitudinal momenta of particles, /79 we can notice one feature which is characteristic just of the "ladder" diagram of the process. By "aligning" all created particles according to increasing longitudinal momentum, we must obtain a resemblance of a geometric series when each subsequent momentum is larger by roughly the same factor than the preceding one. For not very small longitudinal momenta, the same geometric progression must also be valid for the total momenta of the particles. If one considers that the form of a geometric progression depends neither on the multiplicity N nor on the initial energy (i.e., the relation of the next momentum to the preceding one stays constant), then there must be the same fixed arithmetic progression on a logarithmic scale of energy and, besides, a proportionality between the average number of created particles and the incident energy $\bar{N} \sim \lg E_0$.

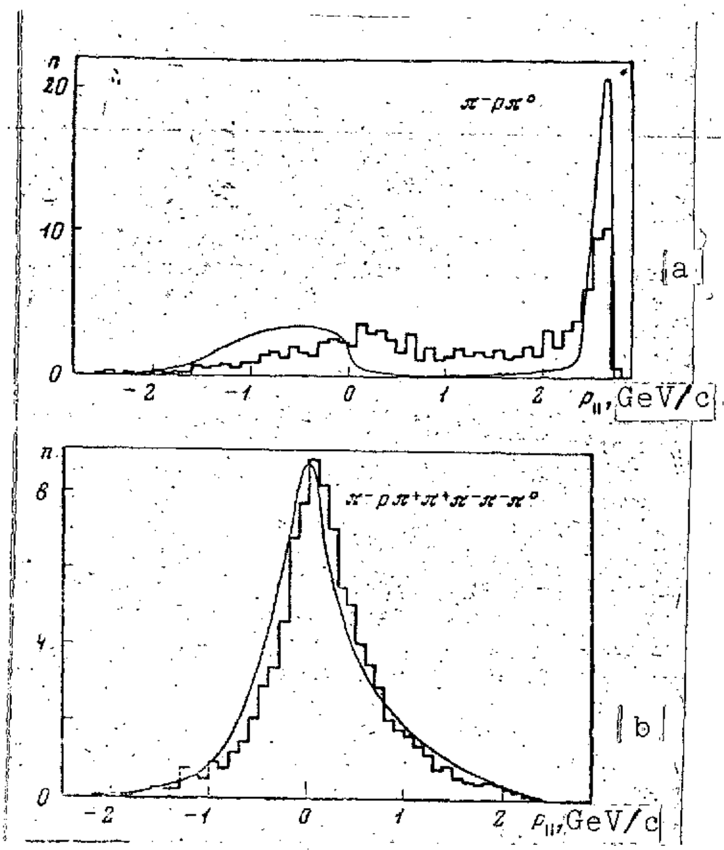

Figure 27. Distributions of the longitudinal momenta of pions created in π^-p interactions of different multiplicity (incident momenta is 16 GeV/c):

Broken lines — experimental results; smooth curves — predictions of the peripheral model for the reactions $\pi^-p \rightarrow \pi^-p\ \pi^0$ (a) and $\pi^-p \rightarrow \pi^-p\ \pi^+\pi^+\pi^-\pi^-\pi^0$ (b)

Besides the longitudinal component of particle momentum $(p_\parallel)$, the transverse component $(p_\perp)$ is also important since this quantity does not depend on the choice of coordinate system. The quantity:

$$y = \frac{1}{2} \ln \frac{E - p_{\parallel}}{E + p_{\parallel}}$$

called the rapidity (y) also plays a special role in the theoretical analysis of experimental data.

At first, this quantity did not appear to be very attractive or normal, especially to the experimenters. However, by means of several mathematical transformations (which we leave to the reader), one can verify that the scale of rapidity closely corresponds to the logarithmic scale of angles θ, namely,

$$y \simeq \ln \mathrm{tg} \frac{\theta}{2}.$$

This already allows a comparison of theory with experiment without recourse to measurements of momenta (or energies) of the created particles by limiting oneself to angle measurements.

By means of another transformation, one obtains a different expression, which is simple and approximate, for the rapidity:

$$y \simeq \ln \frac{2E}{m_{\perp}}.$$

Here, E is the energy of the created particle, and $m_{\perp} = \sqrt{p_{\perp}^2 + \mu^2 c^2}/c$ /80

does not depend on the choice of coordinate system but, however, depends on the nature of the particle, namely on the mass μ (c is the velocity of light).

In this fashion, when energy (or momentum) measurements are available, one can use the scale of rapidity as a logarithmic scale of energy, but only with the proviso that the units of measurement of this scale depend on the mass μ and on the transverse component of the particle momentum $p_{\perp}$*.

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*For real values of $p_{\perp}$, which are small compared to the proton mass multiplied by the velocity of light, the quantity y for the proton is almost independent of $p_{\perp}$.

An important advantage in introducing the rapidity instead of the longitudinal momentum or the energy is that, in the case of a transformation from one system of coordinates to another which differs to an arbitrarily large degree in the velocity of its motion in the direction of the incident particle, the rapidity of all secondary particles (independent of their velocity or mass) changes by one and the same constant. Consequently, any arbitrarily complex distribution of these particles in rapidity preserves its form exactly for such a transformation. It only moves left or right on the scale of rapidity.

Still another merit of this quantity, as later experiments on the accelerators of higher energy showed, is that with a change of the rapidity (in contrast to the longitudinal momentum) of the average transverse momentum, the entire distribution of transverse momentum remains unchanged. In this way, the rapidity and the transverse momentum constitute two complementary invariant characteristics of particle production.

Calculations using the peripheral model show that for sufficiently high incident energies, the distribution in rapidity of created particles must have a simple, "table-like" character (Figure 28). In this case, the rapidity itself forms an arithmetic progression, and the "width" of the table and the number of particles produced is proportional to the logarithm of the incident energy and, consequently, to the rapidity of the incident particle.

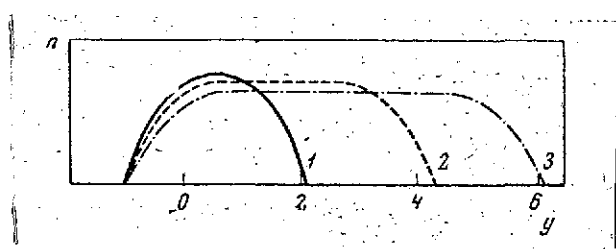


Figure 28. Predictions of the multiperipheral model of the change in distribution of secondary π^--mesons as a function of rapidity y in the interaction $\pi^+ + p$ as the rapidity of the initial π^+-meson y_0 changes (y_0 = 2, 4, and 6) /81

In some cases, azimuthal angles are analyzed. These are the angles between the transverse momenta of the particles, obtained from the projection of the momentum on the plane perpendicular to the direction of the incident particle. If, for processes of the multiperipheral type, we "align" the particles in order of increasing longitudinal momentum, then we thereby progress along the "ladder" in the diagram shown in Figure 23a. In this case, each particle must have reacted stronger than ever to the emission angle of its nearest neighbor, experiencing (if only partially) the corresponding recoil in the equatorial plane. Detailed analysis of the expected angular correlations showed that effects of such a type do not exist. The impression is made that independent of the longitudinal momentum received, the scattering of all the pions occurs as if from one center of emission. Unfortunately, with increasing initial energy and the corresponding increase in multiplicity of the process, the electronic computer must sort through an ever larger number of different combinations of particle momenta. Indeed, tens of hours are spent on calculations even for the relatively moderate energy of $E_0 \sim 30$ GeV. It is not surprising that many physicists are seeking an escape from "constructing" other, computationally more complex, models which are based not on the sequential exchange of chains of virtual particles, but on a more or less equal "mixing" of created particles.

CHAPTER 5. STATISTICS, HYDRODYNAMICS, AND THERMODYNAMICS "WITHIN" ELEMENTARY PARTICLES

Phase Space — The Cornerstone of Statistics

In proportion to the increase in energy of the created particles in inelastic collisions of hadrons and, parallel to this, to the total number of particles produced, difficulties increase with the theory of peripheral processes. It is necessary to consider an ever larger number of reaction channels, i.e., the various combinations of secondary particles of different nature. Consequently, even with the use of powerful computers for calculating all the concrete possibilities (say, for example, in the multiperipheral model), tens and hundreds of hours of pure calculation time are required. The abundance of parameters — the numerical characteristics governed by the behavior of the virtual particles — also interfere. Indeed, these must be "fit" to the experimental results. /82

On the other hand, scientists began to observe such hadron collisions (especially those involving complex nuclei) long ago in cosmic rays in which tens and even hundreds of particles are created simultaneously. One would think that in such cases, i.e., in averaging over a large number of possible directions, velocities of emission, and internal states of the created particles, definite regularities would begin to express themselves.

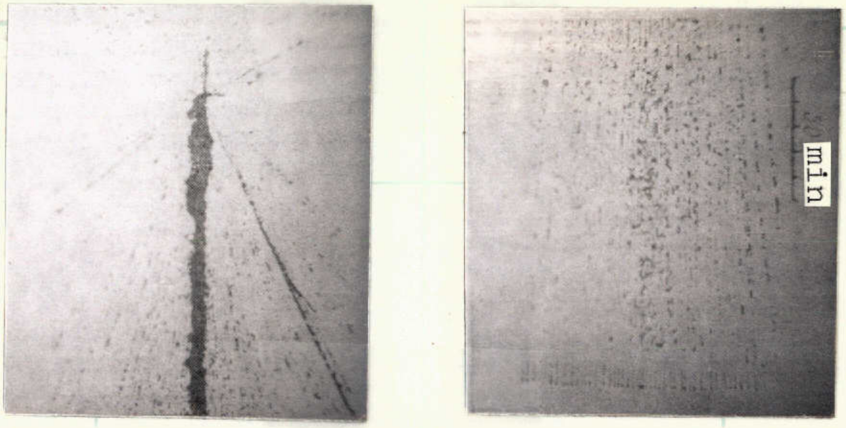


Figure 29. Photoemulsion copy (micrograph) of a rare process of production of $\sim$ 330 charged particles by an initial heavy nucleus of cosmic radiation of energy $\sim$ 200 GeV/nucleon. There is an interval of 650 minutes between the left and right parts of the photograph in order to be able to show the separation of the dense central part from the tracks of the other particles. The scale of the photo is at the right

Regard carefully Figure 29. At first glance, the various kinematical possibilities of particle emission (i.e., the possibilities of emission at different angles and with different velocities) are far from being equally probable: all the particles move within the limits of a relatively narrow cone, and among them there are practically no slow particles, which distinguish themselves by higher density tracks. This situation changes significantly if all the kinematical descriptions of the process are carried out in a moving system of coordinates (c.m. system), in which the total momentum of the colliding particles is equal to zero. In order to make the transformation to this system of coordinates, it is necessary to use the formulas of the special theory of relativity, which are called Lorentz transformations. /84
In the simple case when one is concerned only with the zenith angle θ, and when the particle velocities in the c.m. system are sufficiently close to the velocity of the center of mass, the Lorentz transformation has the form:

$$\mathrm{ctg}\,\theta_L = \gamma_C\,\mathrm{ctg}\,\frac{\theta_C}{2}.$$

In this formula, θ_L and θ_C are the angles of emission of the particle in the stationary system (lab system) and in the c.m. system, respectively; and the quantity:

$$\gamma_C = 1/\sqrt{1-(v/c)^2},$$

is related to the center of mass velocity v, expressed as a fraction of the velocity of light c, and is called the Lorentz factor. If one takes the logarithm of the formula which was introduced above, then it is obvious (Figure 30) that any distribution of particle angles θ_C is transformed to a distribution of the angles θ_L just considered by means of a parallel translation without deformation.

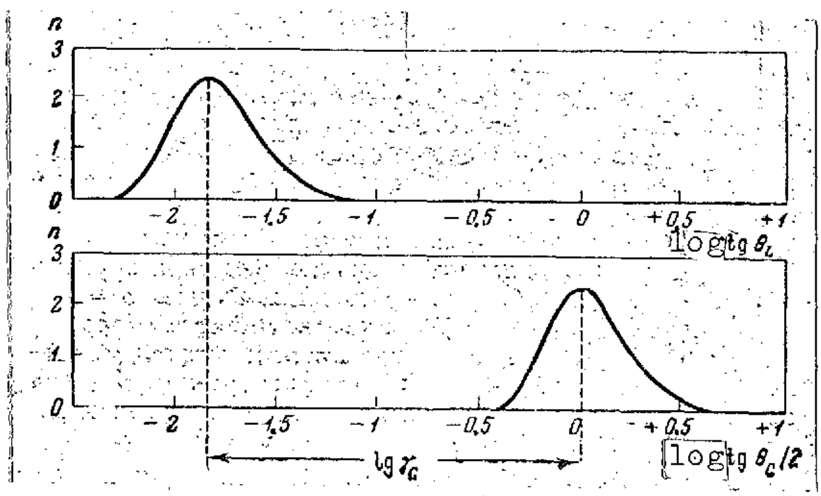


Figure 30. Comparison of the angular distribution of created particles in the laboratory system of coordinates (upper) and the center-of-mass system (lower). The distribution is displaced (without distortion) to the right by an amount log γ_c, where γ_c is the Lorentz factor of the center of mass

The transformation of angles carried out here allows any experimenter to kill two birds with one stone. First, he can determine the "true" (i.e., relative to the c.m. system) form of the angular distribution of created particles. Second, the velocity of the c.m. system is determined, and thus the energy E_0

of the incident particle, according to:

$$E_0 \simeq 2\gamma_C^2 M$$

(the mass of the incident particle M is assumed to be the same as the mass of the stationary target, e.g., a nucleon).

After applying the Lorentz transformation to the event shown in Figure 29, one can verify that in the c.m. system the angular distribution of the particles is isotropic, i.e., any emission angle is equally probable.

Besides the angles, the most important kinematical characteristic of the created particles is the momentum $p = mv$, where the mass m is a simple function of the velocity v. The mass m differs from the constant rest mass by a factor equal to the Lorentz factor γ. One cannot simply assume that any momentum is equally probable, since the momentum is related to the energy E /85 (at high velocities, p and E are numerically equal and differ only by the choice of units of measurement), and the total amount of energy is limited by that of the incident particle. However, it is completely natural to think that, within the maximum limit of momentum allowed by momentum conservation, all possible values of momentum are equally probable.

Since momentum is a three-component vector quantity, equal probabilities of the directions and magnitudes of the momenta imply a uniform population of the volume of a sphere of radius $r = p_{max}$. This sphere is conventionally represented in an abstract space which is called phase space. Besides the three usual geometric coordinates, phase space also has an additional three along which momentum is plotted.

Once we go beyond the limits of three-dimensional space to a system of N particles, we increase the number of dimensions to 6N, and thereby move from normal space to phase space. This physical-geometrical "focus" can be used with success in studying elementary particles. For this it is necessary to postulate, as did first G. V. Vatagin, in 1943, and then E. Fermi in greater detail, that in the case of particle production the phase volume of a system of an arbitrary number of particles N is uniformly populated with a density determined by the specific concentration of energy in the initial state of the colliding particles. The energy density of this state can be determined by knowing the total energy of the colliding particles in their c.m. system and the radii of these particles which are specified by the radius of the strong interaction.

By using the idea of the uniform occupation of phase space, Fermi was able to calculate not only the average energy of the particles (and, consequently, the temperature of the system at the moment of disintegration), but also the number of created particles and anti-particles of different mass.

In the calculations of Fermi, another important fact was taken into account. According to the theory of relativity, any rapidly moving body is contracted in its longitudinal (in the direction of motion) dimensions. The coefficient of this contraction is equal to the Lorentz factor γ_c. Thus, just before the collision we have the situation schematically represented in Figure 31a. After the collision, both lens-shaped particles merge /86
into a "body" which is just as oblate, but now strongly heated up. This object decays into individual free particles, which uniformly occupy all of the phase volume available.

With quantitative comparison with experiment, the hypothesis of Vatagin-Fermi suffered a distinct failure. It predicted temperatures that are too high. The average energy of the particles was calculated to be billions of electron-volts, and this even increased with increasing initial energy. As a result, probabilities that were too high were obtained for the formation of pairs of heavy particles and antiparticles (in particular, anti-protons).

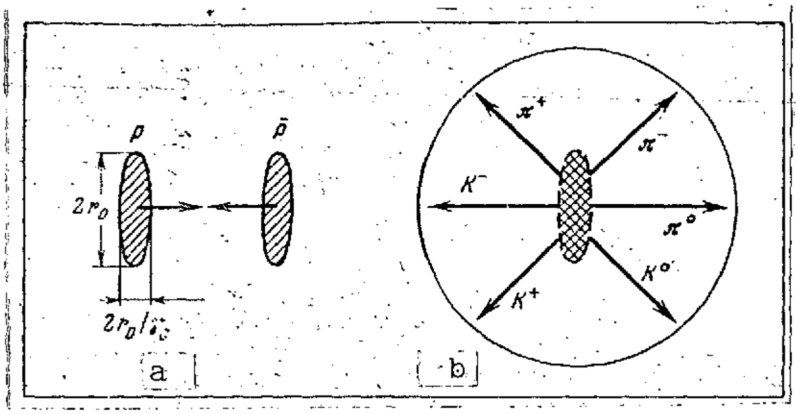


Figure 31. a) Initial state of the interaction process between two hadrons of the proton-anti-proton type; b) the final state of the interaction process of two hadrons of the proton-antiproton type (Pomeranchuk model)

In fact, the average energy of the created particles is close to 0.5 GeV (billion eV). This corresponds to a temperature of "only" 10^{12} degrees, or 10^8 eV in energy units*. The yield of K-mesons constitutes $\sim$ 10% of the total number of particles. The fundamental mass of the created particles is the pion mass. Therefore, the relation between the π^+, π^-, and π^0 particles is actually close to that expected (1 : 1 : 1), especially for a large number of particles when the small initial charge of the colliding particles is not important. /87

*The feasibility of measuring temperature in units of energy is related to the fact that temperature on the absolute scale of Kelvin is proportional to the average particle energy.

In the case of annihilation of stopped anti-particles with one of the protons of a nucleus of the surrounding matter, all the relations are found to be more simple. The total charge and all the quantum numbers of the resulting excited system are equal to zero, the angular distribution of the particles in the lab system is strictly isotropic, the number of particles and anti-particles (in particular, π^+ and π^-) are equal, and the number of π^0-mesons is equal, on the average, to the number of π^+ or π^--mesons. This is a classical case of a blob of strongly excited matter (but not material!) which decays according to the laws of statistics, something like a microscopic, instantly exploding ball lightning (with the distinction that the heating up of the blob is a result of strong and not electromagnetic interactions*). Here again, the average energy of the particles equals 0.5 GeV, and their average number is about 4, since the total mass of two annihilating protons is about 1.9 GeV (in energy units). The "admixture" of K-mesons in this case is $\sim$ 5%, instead of 30% as predicted by the method of Fermi.

In spite of the initial failure, the simple model of Fermi was subsequently found to be very fruitful. It prompted, in particular, the extension of many concepts of physics which, it seemed, were suitable only for states of large numbers of molecules of continuous media, to processes of transformation of elementary particles and, to a significant extent, even to processes occurring within these particles. The concept of the temperature of a system of created particles acquired a real physical sense. The use of the laws of thermodynamics was also justified. The point is that thermodynamics deals with the equilibrium (or

*According to the current conception, ball lightning is a blob of strongly heated plasma existing in a relatively stable state (there is a hypothesis which states that the stability is provided by the isolation of the ions from one another by means of complexes of water molecules).

near-equilibrium) states of a system in which the energy is distributed among many degrees of freedom. This is just the situation in multiple particle production, especially in those cases when a uniform distribution in phase volume is "allowed". Indeed, the laws of thermodynamics, in particular, the law of the dependence of the energy density E on the temperature T ($E \sim T^{1/4}$), allowed Fermi to more or less correctly predict the dependence of /88
the average number of created particles N on the energy of the incident particle E_L ($\bar{N} \sim \sqrt[4]{E_L}$).

The Laws of Motion of the Meson "Fluid" and Transverse Momenta of Particles

Immediately after the publication of Fermi's work, the Soviet theoretical physicist I. Ya. Pomeranchuk discovered some inconsistencies and even contradictions in Fermi's work. In fact, the conversion of all the energy of the colliding nucleons into mesonic radiation occupying the same volume as the nucleons requires a very strong, practically infinite inhibition in the continuous interaction of the nucleons. At the same time, the total energy of the created particles is calculated as if they had instantaneously been converted to free particles without having been able to disperse. Meanwhile, it is known that mesons interact with one another almost as strongly as nucleons. Therefore, an intermediate stage of the interaction, which is accompanied by mutual absorption and variation in the number of mesons, must continue until they disperse to a distance r from one another — which is on the order of two strong interaction distances, i.e., $r \sim 2/\mu c$, where μ is the pion mass.

In this way, Pomeranchuk arrived at the assumption of the existence of an intermediate stage of expansion and cooling of the entire system (Figure 31b) to a temperature at which the average pion energy differs by only a small factor ($\sim$ 3.5) from its rest energy (μc^2), and is already insufficient for creating new pions.

While considering Pomeranchuk's work (even before it was published), another prominent Soviet physicist, L. D. Landau, turned his attention to still another important fact. In the process of expansion of the blob of initially condensed and strongly overheated matter, which gives off free mesons similar to molecules of vapor from a boiling liquid, the individual particles must experience an acceleration due to the effect of the mutual pressure of the particles. Since the mean free path of interaction of the particles in this blob does not exceed the /90 distance between them, and since there is no regular spatial structure, it is logical to consider that the state of this matter is similar not to a gaseous, nor to a solid, but to a liquid state. Thus arose the idea of applying the laws developed at one time in hydrodynamics (the theory of moving fluids), in particular, the laws for the relativistic case when the velocity of the moving fluid is close to that of light.

By performing a series of elegant and orderly mathematical operations, Landau obtained the basic features of the process of multiple particle production at sufficiently high energies ($\sim 10^{12}$ eV) from the hydrodynamic equations. This time, the requirement of "sufficiently high" energy essentially implies the requirement of a sufficiently large number (if only about 10) of created particles.

The theory of Landau evoked great interest because it predicted in a totally natural manner the values of the transverse (relative to the direction of motion of the colliding particles) component of the momenta of the created particles. As the numerous studies of nuclear interactions in cosmic rays and then on accelerators subsequently showed, the average transverse momentum of particles $\bar{p}_{\perp}$ depends weakly on their mass, and is almost independent of the conditions of formation. Thus, it does not depend on the number of created particles, the angle of their dispersal, nor the energy of the initial particle. At the same time, the simple statistical model predicted a quite noticeable drop in $\bar{p}_{\perp}$ with increase in multiplicity (Figure 32). The physical principle behind the approach to constant or at least essentially limited values of transverse momenta is, according to the theory of Pomeranchuk-Landau, the constancy of that final temperature at which the divergence of the created particles in a free state occurs.

Specific distribution functions of transverse momenta (for given values of longitudinal momenta) are shown in Figure 33. They pertain to interaction energies of about 20 GeV. This function first increases from zero to a maximum, the most probable value, which is simply related to the increase in phase volume, i.e., the number of possible positions of the two-component vector of transverse momentum in space. After the maximum, there occurs a rapid decrease according to the exponential law characteristic of the thermal motion of the particles. In this case, by selecting particles of higher longitudinal momenta, we also /91
get higher transverse momenta (on the average). As is evident from the figure, the theory agrees quite well with experiment.

The fact that the value of the average transverse momenta of the created particles is constant and usually lies in the region of 0.3 - 0.4 GeV/c, is of important methodological significance for experimenters. This allows one, by measuring only the angles θ of emission of charged particles, to approximately evaluate the total energy liberated in a given interaction by the formula:

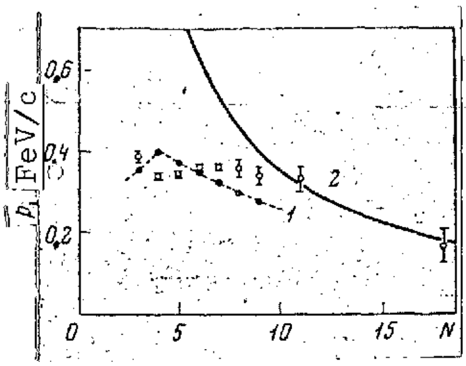


Figure 32. Dependence of the average transverse momentum $\langle p_{\perp}\rangle$ on the number of created particles (N) for $\pi^{-}p$ interactions at an energy of 16 GeV:

Ⓘ — data of the Krakow group; 1 — prediction of the multiperipheral mode; 2 — calculation based on the statistical model

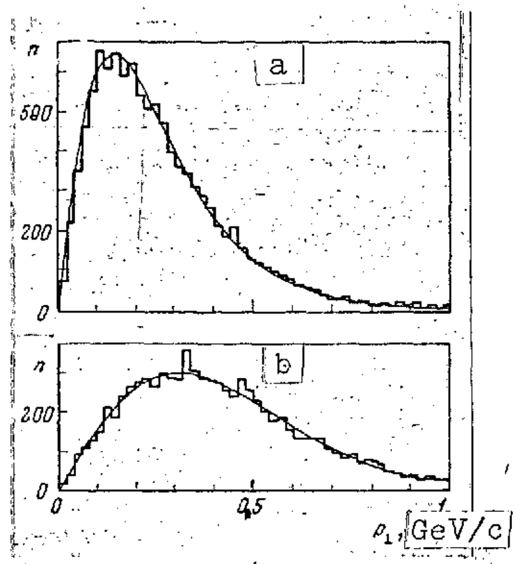


Figure 33. Experimental distribution of transverse momentum $\langle p_{\perp}\rangle$ for longitudinal momenta $\overline{p}_{\parallel}$ = 0.2 GeV/c (a) and $\overline{p}_{\parallel}$ = 1.0 GeV/c (b) for $\pi^{+}p$-interactions at an energy of 18.5 GeV compared to the Planck distribution for a temperature of 118 MeV (in energy units)

$$E = \frac{3}{2} p_{\perp} c \sum \operatorname{cosec} \theta_L,$$

in which the factor 3/2 takes into account the usually unobserved π°-mesons. If the question arises as to the angle θ_{max} at which one should look for the particles created with the minimum energy E_{min} = 10 GeV, then by using the distribution function of transverse momenta and selecting the region which contains 95% of the particles, one can thereupon make use of the relation:

$$\sin\theta\max = \frac{P_{\perp\max}}{E_{\min}} \simeq 0.1, \text{ from which is obtained } \theta_{\max} \simeq 6^{\circ}.$$

Detailed measurements of the transverse momenta of particles (including π°-mesons) have been carried out using both cosmic rays and accelerators for a wide range of initial energies. The behavior of typical results is shown in Figure 34. The graph indicates the integral distribution of the square of the transverse momenta, i.e., the number of secondary charged particles (pions) having values of $p_\perp^2$ greater than the given value. It is obvious that with increasing initial energy, the transverse momenta increase and, consequently, also the temperature of the meson fluid. The highest series of experimental points, which corresponds to the enormous energy $\sim 10^{15}$ eV, agrees very well with the theoretical prediction.

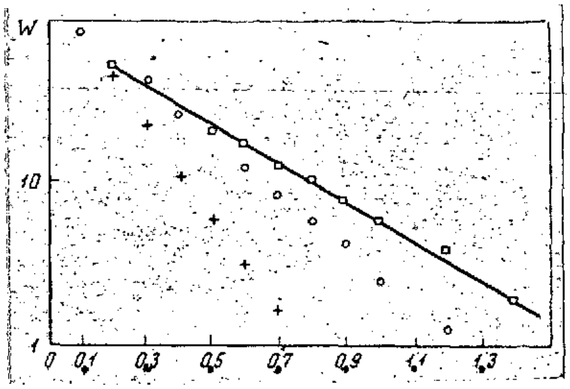


Figure 34. Integral distribution of the quantity $p_\perp^2$ (GeV^2/c^2):

W — number of particles with square of transverse momentum greater than given value for different primary energies E_0; + — $E_0 < 6$ GeV; o — $E_0 > 10^3$ GeV; □ — $E_0 \sim 10^6$ GeV. The smooth curve represents a calculation based on the theory of Landau for $E_0 = 10^6$ GeV

A second achievement of the hydrodynamic theory is the explanation of the anisotropic (non-uniform) distribution of the angles of divergence of the particles in the c.m. system. In fact, the longitudinal components of momenta, according to the theory, depend, in contrast to the transverse components, not only on thermal (i.e., chaotic), but also on directed motion produced by the pressure of the initial condensed state and subsequent expansion of the blob of excited meson fluid. This occurs /92 as a result of the strong collision of the "flattened" initial particles and their "agglomeration". This collective acceleration leads to a preponderance of emission angles near 0° and 180° over those near 90°. On a logarithmic scale of angles, this phenomenon is reflected in a gradual broadening with increasing initial energy of the bell-shaped distribution which is close to the Gaussian curve well-known to physicists (Figure 35).

Soon after publication of the theory, the book's author, /93
Landau, and his colleagues succeeded in observing a rare event with the aid of a photoemulsion: a α-particle of an energy of about 10^{14} eV created 37 particles. In spite of the relatively narrow opening angle, which is a result of the very high incident energy, of the stream of basically massive particles (similar events even received a special name: "jets"), they emerge in a /94
wide range of angles in agreement with theoretical expectations (Figure 36).

The third prediction had to do with the momentum distribution (spectrum) of the created particles. This distribution, which is in good agreement with experiment (Figure 37), has the appearance of a sharply falling curve, distinguished by a marked predominance of particles of relatively low energy. It is interesting to observe that if, instead of plotting the momentum spectrum, one plots the distribution of the flux of energy carried off by the secondary particles of different momenta, then this flux will only weakly depend on energy.

A fourth prediction of the theory is the production of shock waves in the meson fluid. This is related to the fact that the incident particles move toward each other with a velocity significantly in excess of the velocity of sound in the given medium. A similar situation arises in the case of supersonic jets which sometimes produce the loud noises resulting from shock waves reaching the Earth. The theory requires that the shock wave, moving in the meson fluid after a collision, be "splashed out" in the form of a very small number (1 - 2) of "leading" particles, each one carrying off energy amounting to tens of percent of the

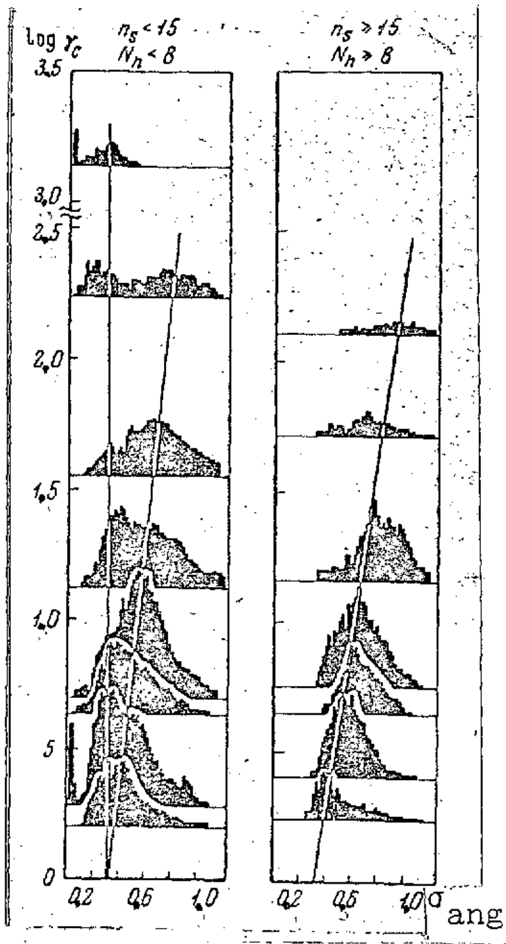


Figure 35. Increasing anisotropy σ_{ang} of the angular distribution of created particles (the width of the distribution on the logarithmic scale is the measure of the anisotropy) with increasing energy of the incident particle (γ_c, the Lorentz factor is a measure of the energy in the center-of-mass system):

n_s — number of fast secondary particles; N_h — number of slow secondary particles

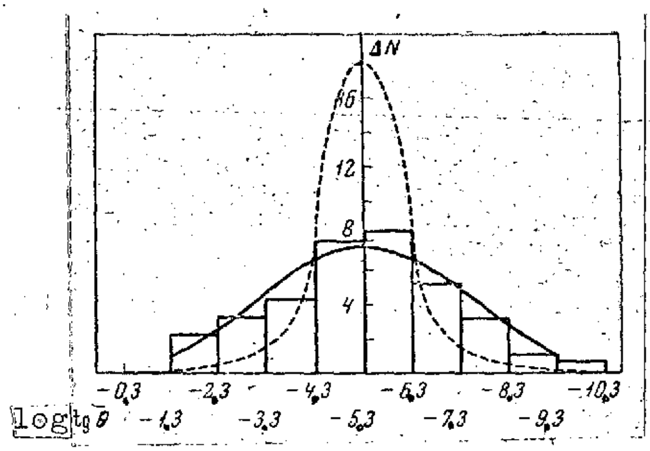


Figure 36. Experimental angular distribution of particles in a photoemulsion "jet" of the type $(1+0+37\alpha)$ (produced by an α-particle of energy $E_0 \sim 8 \cdot 10^{13}$ eV) compared to the theory of Landau (continuous curve) and the isotropic distribution (dashed curve). Data of I. M. Grameni-tskiy et al., FIAN

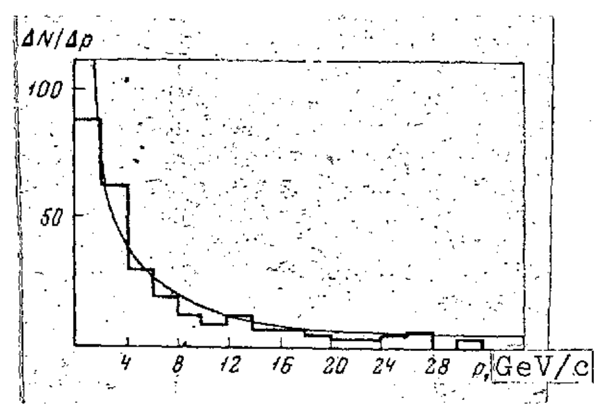


Figure 37. Momentum distribution of created particles at energy of $\sim$ 300 GeV (data of N. A. Dobrotin et al., FIAN) and comparison with calculations based on hydrodynamic model (E. I. Daibog, L. I. Rosental)

initial energy. In the case shown in Figure 36, this leading particle is the neutral pion which initiates (after decaying into two γ-quanta) a powerful electron avalanche. This can be easily seen in photoemulsions, even with the unaided eye.

According to theory, a particle of any type, be it a proton, a neutron, or a π-meson of any charge, can become a leading particle with equal probability. The probability of being a "leader" for each of these particles does not depend much on the nature of the incident particles since in the process of expansion of the "boiling" meson fluid each individual particle is agitated, and it is necessary to consider only the law of baryon conservation. The theory imposes a single constraint on the number of particles heavier than the meson. This is related to the relatively low temperature to which the meson fluid cools when expansion ceases.

An Examination of the Starting Points of the Hydrodynamic Theory

The work of Landau, with its very rigorous and detailed calculations of the fundamental characteristics of the process of multiple meson production, initiated a lively response among physicists, especially theorists. First, the question arose as to why several results differed markedly from the predictions of another hydrodynamic model proposed by Heisenberg shortly before Landau's, but which was not developed in such detail. In particular, the number of created pions in Heisenberg's model was larger and increased more rapidly with increasing incident energy (as root-three and not root-four of this energy). Finally, it was successfully explained (by a young Soviet theoretician, G. A. Milekhin) that the meson fluid with which Heisenberg "dealt" in his model differed in a fundamental equation of state, namely, the relation between density and pressure. The result of this /95 difference was the "transfer" of a large fraction of the incident energy to the turbulent (vortex) motion of the meson fluid, which is characteristic of Heisenberg's model.

The next question which excited the theorists was whether it was necessary to expect a significant viscosity of the meson fluid, which would be expressed in the process of expansion (after the initial collision), and in the related question of the ultimate number of created particles. If, in the calculations of Landau, which assume an ideal, completely non-viscous fluid, the number of particles increases as root-four of the energy, then the viscosity of the Heisenberg fluid favors a more rapid (proportional to the fourth root) increase of the multiplicity with increasing energy. The form of the angular distribution of the created particles is also changed somewhat (but not strongly).

However, from the point of view of the experimenters, before investigating in detail the behavior of the meson fluid, it is necessary to first resolve a more fundamental problem. This consists of whether one can generally disregard the structure of the colliding particles, a structure which is so important in the investigation of the processes of few particle production. In fact, the first stage of the process, considered from the hydrodynamic point of view, consists of the formation of a single strongly interacting system in which all the energy of the colliding hadrons is "placed". In other words, it is proposed from the /96
very beginning to exclude all peripheral processes from consideration and concentrate on the central collision.

One way of approaching the solution of this problem consists of studying the form of fluctuations, in particular, the distribution law of the deviation of the number of created particles from the mean at a given energy. And exactly in this respect, experiment is in sharp disagreement with the theoretical predictions. It was found that the fluctuations are at least two times greater than expected. This fact, in conjunction with the clear successes of low multiplicity models in describing single particle exchange (especially for not very high energies, up to 10 GeV), gradually strengthened many physicists in the opinion that the hydrodynamic approach, in particular, and the statistical approach, in general, to the phenomena of multiple production of particles is as far as ever from being plausible.

The annihilation of a nucleon with an anti-nucleon belongs to that class of "classical" processes for which the statistical approach describes the real situation well. The characteristics of such a process will be discussed in detail in the next section.

Pondering how the applicability of statistical methods to analysis of multiple production processes could be justified,
I. M. Dremin (FIAN) proposed a simple method, which is, however, /97
tedious from the point of view of mathematical calculation. It is based on the fact that particles, originating with the decay of any common strongly interacting system, must always have the possibility of exchanging large momenta among themselves. Suppose we study the inelastic interaction of two nucleons. We will consider the "mutual relations" of the secondary nucleons with the remaining particles which originate in the total collision. Consecutively grouping the increasing number of mesons in distributions of their emission angles from primary to secondary nucleons, we will calculate the square of the momentum (k^2) each time. This produces an entire group separate from the remaining particles. In order that the calculated result not depend on the choice of coordinate system, four-component vector quantities are considered. The first three components are made up of the

"real" momentum, and the fourth component is the energy. The resulting values of k^2 are plotted along the ordinate, and on the abscissa, the point proportional to the number of particles in the group is marked off. The entire set of points in this fashion from a given interaction lie on a straight line. Data from processes in which four or more charged pions are produced in nuclear interactions at energies of $\sim$ 20 GeV in photoemulsions are plotted /98 on similar graphs (called Dremin diagrams). It was found that in different cases, a Dremin diagram looks different, but it is possible to designate five basic classes of interactions (Figure 38a).

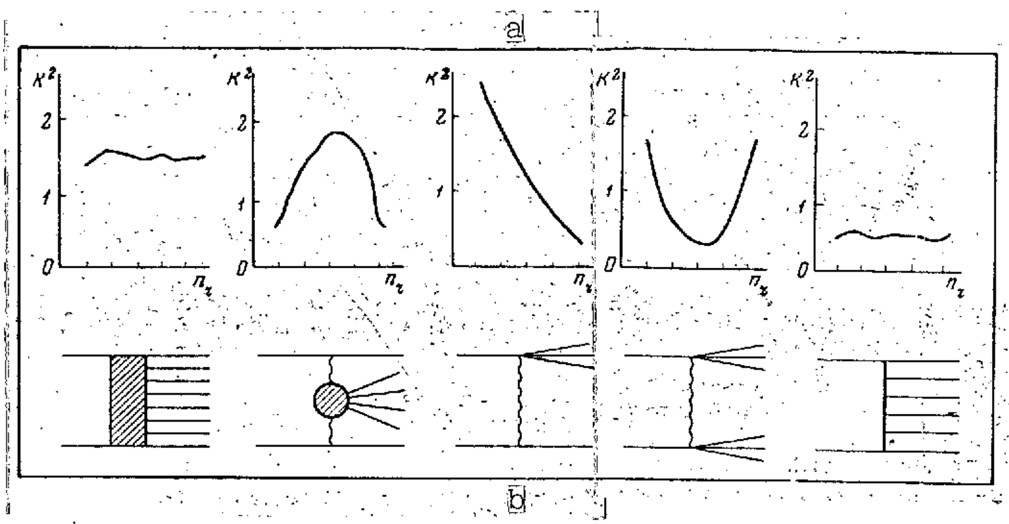


Figure 38. a) Five experimentally observed types of distributions of k^2 (M. M. Chernyavskiy, FIAN): k^2 is expressed in GeV^2/c^2; n — number of particles combined into a group;
b) Feynman diagrams corresponding to these types of interactions

In the first class, the squares of the momenta k^2, which are transmitted to groups having any number of particles are large; in the second class, which is quite rare at these energies, k^2 for individual nucleons is small (what one is concerned with here is the momentum transmitted from the initial proton to the corresponding secondary one), but as the number of pions associated with them increases, the quantity k^2 passes through a quite large maximum; in the third and fourth classes, a gradual decrease of the momentum k^2 is observed in proportion to the increasing number of pions associated with one of the nucleons (or with each one of them).

Finally, the fifth class, which is very common, is characterized by small transmitted momenta between groups consisting of any number of particles: all values of k^2 are significantly smaller than the square of the nucleon mass (in units of momentum).

In Figure 38b, each class is represented, together with its corresponding Feynman diagram. In the first case, a central interaction occurs, i.e., the formation of a single excited system of secondary particles, which then decays according to the laws of the statistical theory. Events of the secondary class have a peripheral character for each of the colliding particles, but in collisions of the virtual particles emitted by them, several new subsystems are created which subsequently decay in the statistical fashion. The third and fourth classes represent collisions accompanied by strong excitation of one or two nucleons and their subsequent decay.

Events of the fifth class are very similar to those predicted by the multiperipheral model, since all the values of k^2 transmitted along the chain of virtual particles are of the order of the square of the pion mass.

This, then, is a new approach to explaining phenomena by means of theoretical models of a hybrid type which combines specific features of both peripheral and central interactions.

We will discuss one model of this type in the next Chapter, but now we return to the possibility of using the laws of thermodynamics.

Can One Manage with Only the Laws of Thermodynamics?

We have already discussed how the statistical theory is based on the idea that all regions of the volume in the phase space of particle coordinates and momenta, allowed by the conservation of energy, are populated with equal probability. The normal geometric part of this volume V is given, in agreement with the basic idea of Pomeranchuk, by: /99

$$V = \frac{4}{3} N \frac{\pi \hbar^3}{(\mu c)^3},$$

where N is the number of created particles, and μ is the pion mass. The physical significance of the factor $4\pi/3$ is very simple. It is the volume occupied by a single free particle since the quantity $\hbar/\mu c$ is simply the radius of the strong interaction. Strictly speaking, this radius, determined by the uncertainty relation of quantum mechanics, is known only to within a factor on the order of 1, but from comparisons with experiment, it follows that this factor can be taken equal to 1 with quite good accuracy.

In addition, we must realize that we are dealing not with normal, but with quantum statistics, for which a particle of each type is "assigned" a cell in phase space of volume $\hbar^3 g_i$ (the factor g_i denotes the number of possible spin orientations, for example, in the case of pions, $g_i = 3$).

And finally, the third, decisive factor, which expresses the very essence of the thermodynamic model, is represented in the simplest case by the factor:

$$f(E,T) = 1/(e^{E/kT} \pm 1)$$

and determines the degree of occupancy of the cells in phase space by the created particles at a given particle energy E and system temperature T (k is the Boltzmann constant). This factor carries a sign of plus or minus, a consequence of the fact that all particles of the microworld can be divided into two basic "types". For particles with integral spin (e.g., pions), the plus sign is always used; for particles with half-integral spin (e.g., nucleons), the negative sign is always used. The physical significance of the factor f (E, T) is that by means of "contact" with a surrounding heat reservoir (i.e., with other particles and fields), a given particle can assume any energy E with a probability depending on the energy of thermal motion of the specific system.

The final expression for the number of particles of a given type having a momentum $\vec{p}$ in the interval $\Delta\vec{p}$, is:

$$\Delta N_i = \frac{g_i}{h^3} V \Delta\vec{p} f(E,T);$$

If the temperature is known, then by summing (or more precisely, by integrating) this expression over momenta, one obtains the total number of created particles N_i and their total energy E_i. If the temperature is not known, it is possible to determine it approximately, since we know from experiment that the principal part of the energy of the entire system is shared by the particles of minimum mass, the pions. By disregarding the contribution of other particles and setting the energy of the pions equal to the initial energy W, one can determine both the mean pion $\bar{E}$ and the temperature T. They are equal to 0.43 and 0.135 GeV, respectively.

In order to transform units of energy into degrees Kelvin, it is necessary to multiply the temperature values expressed in electron-volts by 11,600 degrees/eV. As a result, the thermodynamic model predicts that the multiple production of particles should occur at a characteristic temperature of $1.6 \cdot 10^{12}$ degrees (1.6 trillion degrees).

In order that the hydrodynamic effects, which are related to the accelerating action of pressure and the presence of shock waves in the meson fluid, appear in full degree, it is necessary to have a sufficiently high initial energy and many (not less than 10) created particles. Therefore, in order to properly test the thermodynamic process uncomplicated by the influence of pressure, it is useful to turn to the "classical" example like the annihilation of nucleons and anti-nucleons at a total energy of not more than 5 - 6 GeV in the c.m. system. This is just the region which has been studied in detail with the aid of proton synchrotrons of the Dubna and CERN types. In 15 experiments of a similar type, the energy of the created particles has been measured, and it was found to be 0.41 GeV, on the average. This agrees with the theoretical predictions to within an accuracy of 5%.

But what happens in situations not so clear when the applicability of the thermodynamic model is far from being evident? /101 In order to answer this question, one can utilize (as did E. L. Feinberg recently in his detailed review) the data of nucleon-nucleon interactions at an initial energy of 10 GeV and higher, and pion-nucleon interactions at energies ≥ 4.5 GeV. The average energy of the created pions was found to be 0.46 GeV in the first case, and 0.54 GeV in the second. It is suspected that the excess of these values over the predictions of the thermodynamic model is related to the "impurity" of the particles created in peripheral channels. The diagrams 1, 3, 4, and 5 in Figure 38b give a schematic representation of the characteristics of these channels.

The situation is more complicated in comparing the average number of created particles rather than the average energy. In this case, one has to take into account the fact that the "leading" secondary particles, which do not participate in the thermodynamic equilibrium, carry off a significant part of the initial energy. If we assume that this fraction is 60%, we can achieve approximate agreement of the thermodynamic model with experiment. The number of charged pions created in nucleon-nucleon collisions at energies of 20 - 30 GeV is about 4, on the average.

At higher energies of the colliding particles (on the order of 100 GeV and higher), not even a rough calculation of the peripheral "channels" helps: the average energy of the created particles (relative to the c.m. system) begins to steadily increase in clear contradiction to thermodynamics. The hydrodynamic model explains this increase by saying that the pressure of the expanding meson fluid leads to a distinct collective acceleration of the particles in the direction of the collision axis.

Is it possible to improve agreement with experiment within the framework of thermodynamics alone? Two attempts in this direction have been undertaken by physicists.

The first attempt was to introduce in a purely formal manner two temperatures — a transverse and a longitudinal — so that the longitudinal one would somehow account for the influence of collective acceleration. It was found that at energies on the order of 200 - 500 GeV, it was sufficient to increase the equivalent longitudinal temperature by a factor of 1.5 - 2 relative to the transverse in order to obtain all the momentum and angle characteristics of the created particles (in their mutual c.m. system).

The second, more complex attempt was made by the Swiss R. Hagedorn and his school. They took into consideration not one, but an infinite number of excited subsystems, which decay according to the laws of thermodynamics (Figure 39). The masses of these subsystems can be different: beginning with one pion mass and increasing to the maximum possible, consistent with the given collision energy. In addition, they assumed that the number of possible states (and corresponding masses) became larger and larger as the mass increased. This assumption is quite natural: first, it agrees with the rapid increase in the number of known resonances in proportion to the transition to the region of heavier particles; and, second, if each subsystem is considered as a "set" of pions, the number of possible variations of the set must quickly increase as the number of "members" increases.

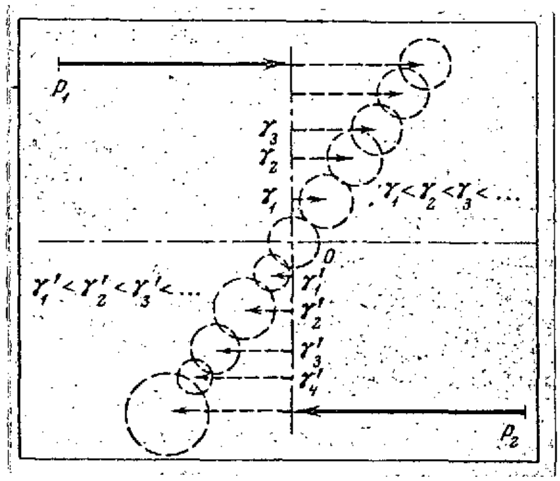


Figure 39. Schematic diagram of the Hagedorn model: p_1, p_2 — momenta of the colliding particles; γ_1, γ_2, etc. — Lorentz factors of the disintegrating excited subsystems in the common center-of-mass system

The second, essential feature of Hagedorn's model is that for each subsystem, the increase of the energy density of the internal motion (as a result of excitations) parallels the decrease in velocity of the system as a whole. Between the initial /103 (before the collision) and final (immediately before the decay) energy density E of the subsystem satisfies the relation:

$$E_0\gamma_0 = E'\gamma'$$

where γ_0 and γ' are the corresponding values of the Lorentz factor [remember that $\gamma = 1/\sqrt{1-(v/c^2)}$]. Thus, the closer to the collision center (point 0 in Figure 39), the larger the fraction of the initial kinetic energy of relative motion of the two "pieces" of matter that is transformed to excitation energy or, in other words, to heat. In order to quantitatively estimate the effect of this energy transformation, a distribution function of the subsystem is introduced. This is a function F (γ) of the Lorentz factor, and the form of this function is determined by the "fit" to experiment. One of the difficulties of the model is that, in order to correctly predict the momenta and angles of the secondary particles emitted, it is necessary to introduce a specific function F for each type of particle. In particular, these functions have a completely different form for nucleons and pions. In this roundabout way, the structure of the colliding particles is taken into account, as are, in part, the peripheral characteristics of the interaction. The complexity of the model is increased by the fact /104

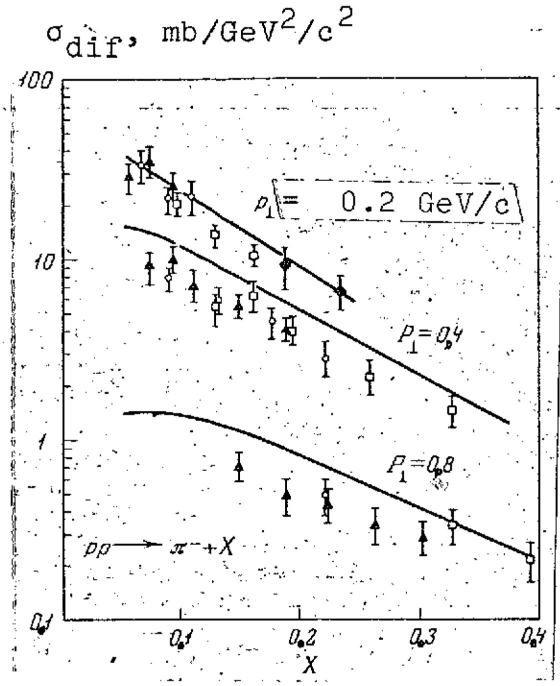


Figure 40. Experimental distributions of relative longitudinal momenta X (for various transverse momenta $p_\perp$) from the colliding beam accelerator (CERN), and a comparison to the calculations of the Hagedorn model (solid lines)

that each of these functions F appears to be dependent on the initial energy.

As shown in Figure 40, the model of Hagedorn describes the basic momentum characteristics of the created particles (in particular, the pion) fairly well up to energies of the colliding particles on the order of 10^{12} eV. Nevertheless, on the whole, this model evokes a feeling of dissatisfaction as a result of a lack of rigorous and consistent structural logic. True, the very idea of forming many excited subsystems (they were given the special name "fireballs") is not very new (this will be discussed in the next Chapter). But the mathematical functions which describe the characteristics of the intermediate subsystems, the fireballs, are artificially introduced, irrespective of any relation to the laws of thermodynamics, to which the decay stage of the fireballs is subjected. The model produced is built on thermodynamics, as physicists sometimes say in jest, with the hands instead of with the head, i.e., by means of "fitting" the experiment, and mainly by introducing a formal mathematical description, unrelated organically to nature and to observed physical objects.

CHAPTER 6. DO FIREBALLS REALLY EXIST?

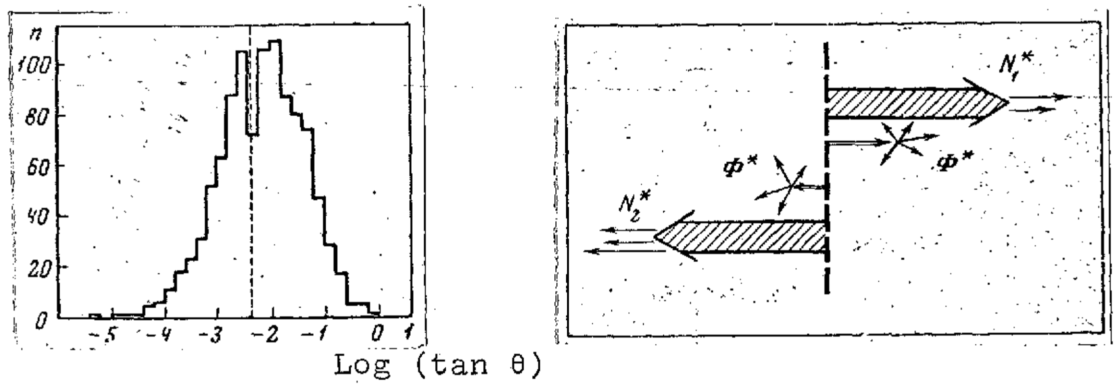
Does "Ball Lightning" Really Appear in Cosmic Rays?

The simplest method of detecting a process of multiple /105
particle production at high energies (10^{12} eV and higher) is to carry stacks of photoemulsion plates by balloon to altitudes of about 30 km in the stratosphere and expose them there to primary cosmic rays. Even with photoemulsion volumes of 2 - 4 liters, it is possible to find many tracks of such processes after developing and careful scanning with a microscope.

Three methods of selecting interactions of sufficiently high energy have been known for a long time. The first is to select the narrowly diverging bundles of particles, the "jets", for which the estimate of energy is based on determining the opening angle of the cone ($\theta_{1/2}$) which subtends half of all the narrow tracks. It has already been noted that this angle is very simply related to the Lorentz factor of the c.m. system of the colliding particles ($\gamma_c \simeq 1/\theta_{1/2}$), and angles $\theta_{1/2} \sim 2 - 3°$ correspond to initial energies of $\sim 10^{12}$ eV. The second method is to find (with suitable skill, even with the unaided eye) dense bunches of almost parallel particles which originate in the photoemulsion as a result of the development of electron avalanches, probably initiated by one secondary π^o-meson of an energy on the order of 10^{12} eV. And finally, one can look for events of heavy nucleus breakup into individual nucleons. They can easily be distinguished from new particle creation. By tracing then the tracks of nuclear fragments (protons, sometime α-particles) along a path of each about 5 cm in length, it is possible to find secondary interactions. In this case, one can estimate the energy of all particles originating in the secondary interaction by the angles of divergence at the point of breakup of the initial nucleons. This phenomenon is somewhat like a miniature, very low power, natural accelerator which puts at the disposal of physicists a beam of 12 - 16 and occasionally more particles (protons and neutrons) of usually a single, approximately known energy.

As early as 15 years ago, a group of Polish physicists from Krakow, under the leadership of M. Ya. Mensovitch, was the first to successfully use the second, and then the third method. Careful measurements of emission angles of particles in nucleon interactions at energies of $\sim 10^{12}$ eV led these scientists to a striking result. The angular distributions of the created particles, plotted on a logarithmic scale of the tangent [log (tan θ)], had, as a rule, a characteristic double-peaked form (Figure 41a). The pattern of the process looked as if the created particles were split into two roughly equal groups, each dispersing isotropically in its c.m. system. Then, by using the law of approximate conservation of transverse momentum, they were able to ascertain that the initial particle, which remains after the interaction, moves more rapidly than all others of the group. From this conclusion, it followed that interactions a high energy proceed by the formation of two blobs of some kind of strongly excited matter which decays practically instantaneously into 5 - 8 charged and probably 3 - 4 neutral pions (Figure 41b). /106 /107

What is the nature of these blobs? If we again use an estimate of the value of the transverse momentum, then we find that each charged particle needs an energy of about 0.5 GeV when the blob decays. This is the same energy which was mentioned in



a b

Figure 41. a) Angular distribution of particles in the combined shower which consists of 54 separate interactions at nearly the same energy. The dashed line corresponds to the angle θ_c = 90° in the c.m. system (data of K. Rybitskiy and V. Vol'ter);

b) Interpretation of the angular distribution with a "dip" near θ_c = 90° in the two fireball model: N_1^*, N_2^* — nucleons after the interaction; Φ^* — fireballs. The long double arrows are proportional to the corresponding Lorentz factors

connection with the previous decay concerning the thermodynamic theory of the process of multiple particle production. In analogy to ball lightning, Mensovitch and his colleagues called the unstable blob of incandescent plasma, which they discovered in 1958, and which explodes soon after formation, a fireball. This same term was proposed independently by Polish physicists and others, in particular, the Italian G. Cocconi and the Japanese K. Niu.

In spite of being unusual, the hypothesis of Mensovitch and his colleagues, who did not penetrate particularly deeply into the thicket of theoretical physics, is attractive because of its simplicity and heuristic value. It allowed a description of the most characteristic features of the phenomenon of multiple particle production, in particular, its angular and energy distributions: the boundedness of the transverse momenta; the transition from an isotropic angular distribution of the particles at low energies (when there is sufficient energy for only one fireball) to one that is anisotropic, being drawn out along the collision axis at high energies; the observable, but nevertheless not very great excess (on the average) of the longitudinal components of momenta over the transverse; and, finally, the existence of leading particles, nucleons which seem to have been "torn out" of the meson "porridge".

As the subsequent experiments of N. A. Bobrotin, S. A. Slavatinskiy and colleagues in the Pamirs showed, only one fireball as a rule is formed at energies on the order of 100 GeV. However, in order to properly "manage" the study of even one fireball, a very substantial apparatus is required, consisting of a large cloud chamber, an impressively heavy calorimeter made up of ionization chambers, and a huge electromagnet to produce a powerful field within the cloud chamber. After many years of collecting and processing the experimental data, which consist (alas!) of only several tens of events at various energies, the following results were obtained (Figure 42). /108

In the c.m. system of the fireball, the momenta of the particles (both positively and negatively charged) are distributed almost exactly according to Planck's Law, which is predicted by thermodynamics for particle

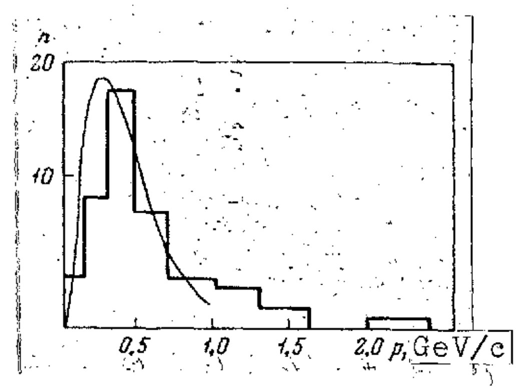


Figure 42. Momentum distribution of particles of the c.m. system of the fireball (broken line) and corresponding prediction of thermodynamic distribution of Planck (smooth line). Data of N. A. Dobrotin et al. (FIAN)

radiation at thermal equilibrium. The word "almost" signifies that the distribution in fact has a small extra "tail" of too large momenta.

The last fact, however, did not confuse the experimenters very much. The point is that a nucleon coming off the fireball can experience, so to speak, a strong "shock" and be excited to one or another resonance state, an isobar. By sorting through the characteristics of the known resonances, it is not difficult to find among them what is needed to explain the momentum and, at the same time, the angular distribution of the particles in the "tail". The behavior of the slower particles, in particular, is explained. They are related to the excitation of the target nucleons.

The schematic diagram of fireball formation shown in Figure 41b differs noticeably from the predictions of the multi-peripheral model (Figure 23b). It gives merely a qualitative explanation of the process and does not enter into the details. This is related to the unavoidably approximate cosmic ray experimental data, which are limited in number. As a result, the traditional skepticism of physicists associated with accelerators in their work overcame from the very beginning the urge to properly verify, prove, or refute the fireball model, which, in their /109
opinion, is not all too rigorous.

Unfortunately, up to 1970, the energy limit of experiments on proton accelerators did not rise higher than 30 GeV; and detailed studies using ion beams were usually limited to energies of at most 16 GeV, since the intensity of these beams decreases quite sharply with further increases in energy. However, even at an energy of 16 GeV (about 5.5 GeV in the c.m. system of the colliding particles), one can count on forming a cosmic fireball since its mean rest energy must at most be about 3 GeV.

Furthermore, the experimenters first of all turned their attention to multiple production processes of a small number of particles (up to 4), which, as a rule, fit well in the scheme of peripheral interactions of the quasi-two particle type, and give more valuable information on the characteristics of various resonances.

Only in the last 5 - 7 years, when the table of known resonances grew to enormous proportions and principally new ideas concerning the explanation of their interrelationships did not appear, interest in many-particle reactions increased. It was natural, in the first place, to use a model diametrically opposed to the peripheral-statistical model with uniform (or more precisely, statistically weighted) distributions of particles in the phase volume.

It became clear quite soon, however, that a purely statistical model is not suitable; in particular, it does not work for most π^--meson interactions. Then it was remembered that the distribution of particles in a cell of phase volume is only a first approximation, which is, generally speaking, optimal. According to the quantum theory of probability, the presence of a particle in one or another part of the "allowed" phase volume is determined not only by the statistical weight, but also by a specific quantity which is formed according to definite rules from the wave functions of the initial and final states of the system, and from a linear operator representing the characteristics of the strong interaction. This quantity is called the matrix element of the interaction. Since a rigorous theory of the strong interactions still does not exist, one merely makes a more or less reasonable /110
guess as to the form of this matrix element.

The simplest guess is that the matrix element is a simple function of the momentum lost by the proton in the process of the πp-interaction. This guess turned out to be very successful. It was found (Figure 43) that the appropriate function F, which rapidly decreases with increasing momentum, complements the statistical model quite well for processes of formation of the most various number of particles in πp-interactions at energies of 8 and 16 GeV.

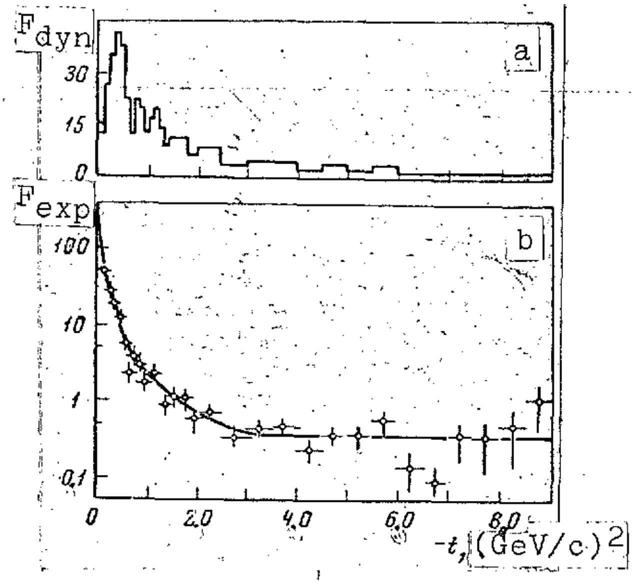


Figure 43. Momentum distributions of the recoil protons in the interactions $\pi^+p \rightarrow p3\pi^+2\pi^-$ at an energy of 8 GeV:

a — directly observed F_{exp}; b — dynamical factor F_{dyn}, obtained from the observed number of events in the corresponding phase space volume

Moreover, this function has roughly the same "pole-like" form as in the case of purely peripheral processes, including the elastic ones. This form reflects the characteristics of the propagator of the interaction, the existence of which (as we have already discussed in Chapter 4) is intimately connected with the transfer of virtual particles, and ensures an increase in the amplitude of the process as the magnitude of the momentum transferred approaches /111 the "non-physical" point corresponding to the mass of the real particle.

A detailed analysis of the experimental data leads to the following conclusion: in the process of multiple particle production in πp-interactions (at least at an energy of 8 GeV), a subsystem is formed which decays according to the laws of "pure statistics" into individual pions. Moreover, there is a separate leading particle, the proton, the recoil of which determines the form factor of the subsystem. It was found that the pion statistical subsystem (sometimes called a cluster, i.e., a blob of particles) is not very different from the already known fireball. Only the value of the average mass of the former is less. One can think of this cluster as if it were an "undeveloped" fireball. For 15 years now, the fierce arguments of the physicists concerning the nature of the fireball, the strange "ball-lightning" glowing at a temperature of a trillion degrees, have not died down.

It looks as if the fireball is an object whose mass (even on the average), in contrast to the heavy resonances, is variable and depends on the conditions of formation. Consequently, the "cursed question" arises with all acuteness: what is a fireball? Since the solution of this mystery has engaged physicists for a long time and with great enthusiasm, we must once again digress into the area or rather abstract concepts and structure of quantum mechanics.

Multi-Peripheral Collisions and the Creation of Fireballs

In Chapters 2 and 4, we have already discussed several of the more common concepts and methods of the quantum theory of strong interactions at high energies. To this pertains, in particular, the energy and momentum (t or k^2) quadratic quantities, the propagator function of virtual particles, which characterizes the dynamics of the interaction process, the amplitude of the process itself, the crossing symmetries between the amplitudes of annihilation processes (s-channel) and scattering processes (t-channel), and finally the profound internal relation between the processes of elastic scattering and the multiple production of hadrons. During the last 5 - 7 years at the P. N. Lebedev Physical Institute, an original approach to the problem of multi-peripheral interactions was worked out by I. M. Dremin, I. I. Roizen, D. S. Chernavskiy, and colleagues. This approach is related to an attempt to separate the contributions of two extreme classes to the multi-peripheral process. On one hand, these are the especially peripheral processes determined by the emission of only one virtual pion (in the case of elastic scattering, two pions), and, on the other, non-peripheral (central) collisions of particles including virtual ones. In the process of solving the problems, an infinite array of sumbolical diagrams of the Feynman type were obtained. Then it was shown that for specific, not very high values of incident energy, which are attainable in current cosmic ray research and in studies using accelerators (up to 10^{12} eV), this array can be limited to a small number of terms. In particular, for proton-proton interactions at an energy of 200 GeV, the four diagrams shown in Figure 44 are found to be decisive. The small squares in the upper and lower vertices in these diagrams correspond to the process of excitation of the colliding nucleons to an isobar state (with the subsequent decay into 2 - 3 particles), and the large square in the middle corresponds to the process of formation of a heavy cluster (a type of fireball), which again rapidly decays into individual particles, in this case, pions. /112

In this specific example, the problem was solved completely, first by calculating the angular and momentum distributions of all the secondary particles, and then by artificially distorting these on the bases of the real conditions, the limitation of the apparatus and the measurement errors. By this method, A. M. Lebedev and S. A. Slavatinskiy succeeded in producing an imitation of multiple production at a rate of 5 - 10 events per minute with the aid of an IBM M-220 computer, and demonstrating complete /113 agreement of the basic characteristics of these events with experimental studies of the same group of processes in cosmic rays.

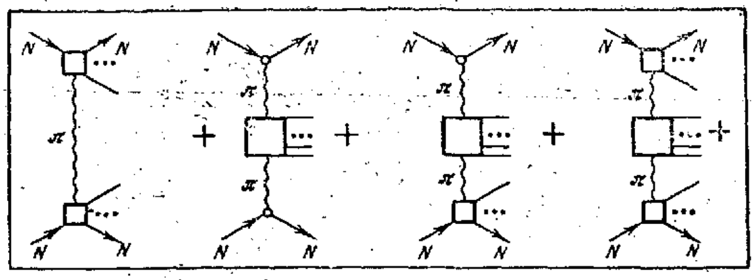


Figure 44. A new variation of the multi-peripheral interaction of two nucleons (N) is represented symbolically by the sum of diagrams, which take into account the exchange of virtual π-mesons, the excitation of nucleons to isobar states (the small squares), and the formation of a fireball (the large squares) with the subsequent decay of the isobars and fireball

In a more general exposition, the multi-peripheral model here makes a series of significant predictions of the number of intermediate structures produced, fireballs, and of their mass. In particular, it was determined that the number of created fireballs is proportional to the logarithm of the energy. The same theory also predicts a logarithmic law of increase of the total number of created particles with increasing energy.

Incidentally, the theory also predicts that the mass of the fireball is proportional to the number of particles into which it decays. On the average, this mass is about 3 GeV (in energy units), and this corresponds to a decay into 6 - 7 pions, on the average. From one event to another, the mass of the fireball can fluctuate about this mean value. In addition, even the average value itself can grow with increasing incident energy until it is no longer "profitable" (from the point of view of the possibility of filling the phase space) to increase the mass of the fireballs or their number.

What is this puzzling object, the fireball, from the point of view of the model discussed here? By analyzing the situation in its entirety, the authors of the model arrive at the conclusion that this strongly excited, unstable system obeys the laws of classical and not quantum physics. The fireball is not a resonance with a fixed average mass and a specific set of quantum numbers, as is characteristic of resonances. Each fireball has a rather ill-defined value of spin, and this may result in a somewhat (though surely not large) anisotropy of the angular distribution of particles (pions) into which it decays.

Furthermore, the anisotropy of the particles emerging after the decay of the fireball can be treated on the basis of the hydrodynamic model by restricting its area of application to virtual particle collisions, and thereby combining the structural (peripheral) approach with the statistical. An important quality /114 of the multi-peripheral model of Chernavskiy-Roizen-Dremin is that, while treating multiple particle production, it simultaneously examines the characteristics of elastic scattering, which are closely related to it, and also makes a series of important predictions in this area. One of the predictions which agrees very well with experiment is the energy dependence of the cone of opening angles, within which particles are emitted in elastic scattering. A series of other predictions (also in agreement with experiment) concerns the basic characteristics of Regge trajectories for the most important virtual particles, and the processes of the elastic (or almost elastic) type which are dependent on them.

Colliding Beams Mean Serious Research

Nevertheless, a decisive test of the fireball model appeared in advance. In order to understand what is meant here, let us consider the main arguments of the opponents of this model. They maintain that the basic features of the process of multiple particle production are determined by at most two facts: first, the limited transverse momenta acquired by all the particles as a result of the strong interaction; second, the isolation in energy of the emitted particles (nucleons, in particular) or, which is the same thing, their limited loss of momentum (in the four-dimensional form).

In fact, only when the longitudinal momenta available for creating additional particles become significantly (if only 3 - 5 times) greater than the transverse, can the "demarcation", which is characteristic of the fireball model, of the strongly excited cluster of particles be expressed in no less than two independently decaying particles. The same peculiarity appeared in the observations of the Polish physicists in the form of a "dip" in the angular distribution of particles for angles near 90° (in the c.m. system). However, the data obtained from cosmic ray experiments are in need of serious verification for several reasons, in particular, because of the paucity of observations and the /116 complex state of the target (photoemulsion nuclei with the additional selection of quasi-free nucleons).

A decisive verification of the cosmic ray data began in 1970, after intersecting beam accelerators started operation at CERN (Geneva). The CERN accelerator allowed the acceleration of protons of energies of 15 - 30 GeV, the storage of the beam in special rings, and then the collision of the beams at the places of intersection of the rings (Figure 45). Such an experimental arrangement has an important advantage over normal accelerators. In this case, practically all the energy of the colliding particles can be expended "usefully" in creating new particles, since it is not necessary to provide for the conservation of a large initial momentum. In this situation, the gain in energy is significant, a factor of 30 - 60, because the total energy W_c in the c.m. system in the case of a stationary target is related to the energy of the incident particle energy and the mass of the target M by the relation $W_C = \sqrt{2E_0/M}$. In addition, the experimenter, almost from the very beginning, carries out his observations practically in the c.m. system of the colliding particles. This fact allows him to measure the angles and the momenta of the particles independently of one another (moreover, these angles are large, and the momenta small, compared to normal accelerators.

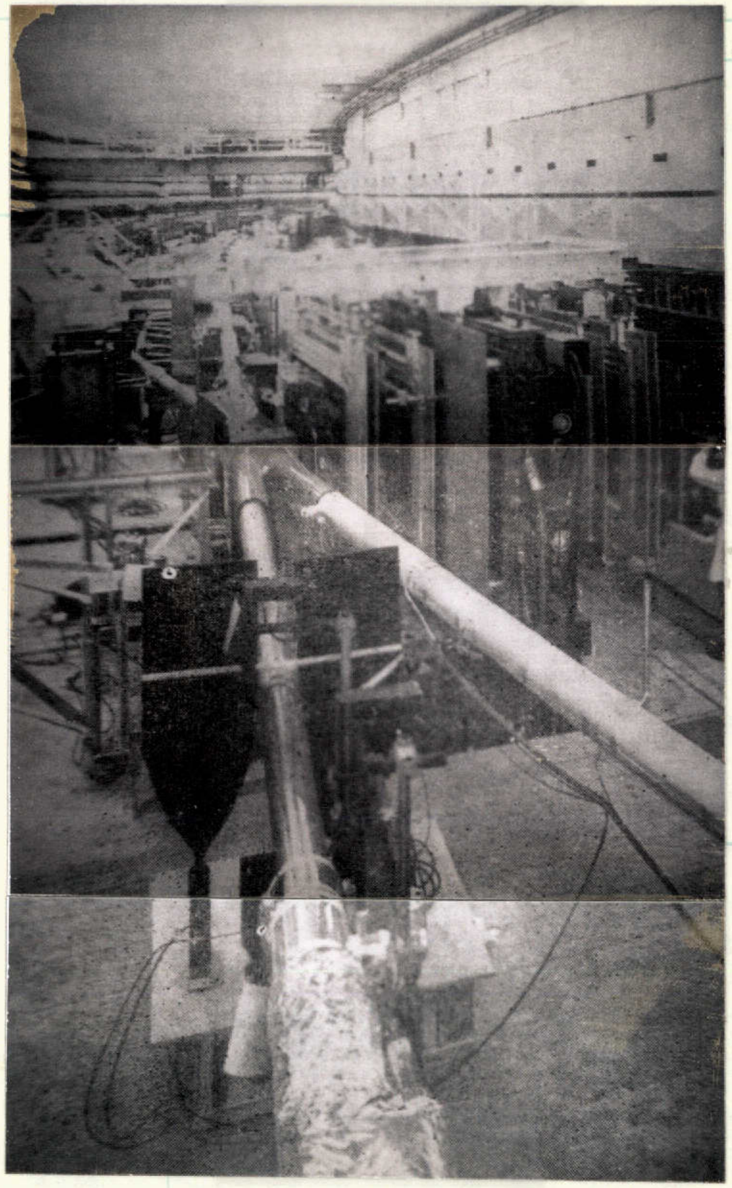


Figure 45. The intersecting rings with their stored colliding beams of high energy protons (CERN)

Polish physicists (G. Gerulya and colleagues) exposed nuclear emulsions in the immediate vicinity of an intersection point of the beams. At first the result agreed well with cosmic ray data: for angles close to 90°, there was in fact a significant "dip" in the angular distribution.

However, it subsequently became evident that there was a disappointing misunderstanding. The secondary particles enroute from the accelerator to the stack of photoemulsions traversed a quite massive iron structure. The π^0-mesons, each decaying into two γ-quanta, succeeded in creating an electron avalanche in the iron. The strength of this avalanche increased with decreasing π^0 emission angle because of the increase in energy.

After removing these obstacles, the measurements were repeated, not only with photoemulsions, but also with the aid of counters. The results obtained (Figure 46) turned out to be a surprise — pleasant for the opponents and unpleasant for the proponents of the fireball model. /117 The angular distribution of the particles, plotted on the rapidity scale $\eta = \ln(\tan \theta_C/2)$ (θ_C is the angle in the c.m. system), has the form of a wide, flat "plateau", without any hint of a "dip" near 90°.

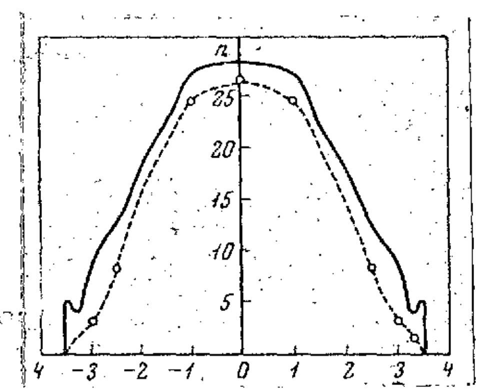


Figure 46. Angular distribution of secondary (charged) particles obtained on the intersecting beam accelerator at an energy of 30 (dashes) and 52 GeV (CERN)

Does the absence of a dip in the angular distribution signify a failure of the entire two-fireball model? The answer of this "tricky" question is far from being obvious, since the predicted dip in angle can, but does not necessarily have to be, a direct consequence of the fireball model. Indeed, the averaging of results of many interactions leads to a smoothing out of the dip, due to a difference in the velocity of motion of each of the two fireballs. Besides, the fact that sometimes only one fireball may be created, leading to a surplus of particles near 90°, facilitates a "washing out" of the dip.

One of the deficiencies of colliding beam machines is the impossibility of direct observation of interaction processes by using detectors which show the particle tracks. There is also the related difficulty of the simultaneous registration of all the products of each colliding particle.

There exists a simple method of by-passing these difficulties which is related to the study of correlations. In the vicinity of an intersection point of two colliding accelerator beams (see Figure 45), we place a counter which registers charged particles leaving at an angle of $\theta_1 = 90°$ to the collision axis. We put a second counter in coincidence with the other, the position of which (angle θ_2) can be changed from one experiment to the next, and which will measure the probability of simultaneous emission of two particles (in particular, a charged particle and a γ-quantum) as a function of the difference in angles, or better, the difference in rapidities. If all interactions occur singly and the interaction is described by the "ladder" diagram of the multi-peripheral model, then the direction of emission of one of the particles "feels" only its nearest neighbor on the "ladder". The angles of emission of all the other particles will be determined by the laws of chance, and this means that the probability of coincidence of the angles θ_1 and θ_2 should be equal to the product of the probability of emission of any two particles at angles θ_1 and θ_2. If one determines the correlation coefficient R, which is proportional to the difference of the pair probability W (θ_1, θ_2) and the product of single probabilities W (θ_1) · W (θ_2), then for a sufficiently large (roughly 10 times) difference in the angles θ_1 and θ_2 it should be zero, and when these /118 angles are equal, it should be relatively small. It is said in this case that the correlations are small and have a "short range" character.*

We now assume that, in fact, a fireball variation of the multi-peripheral model occurs in nature. This is described by the set of diagrams shown in Figure 44. Then the occurrence of a central fireball (the second diagram from the left) will signi- /119 ficantly increase the probability of emission of a second particle at an angle θ_2 near 90°, and inversely, will decrease the probability of angles θ_2 far from 90°. The correlation coefficient significantly increases (approaches 1) near 90°, and passes into the region of negative values far from 90°.

Experiment showed (Figure 47) that approximately such a pattern of large and "long range" correlations actually occurs. Afraid of abusing the two-fireball model in its simplest form, scientists consider that the correlation data indicate a tendency of formation of some kind of massive glob ("cluster") of particles in the process of multiple particle production.

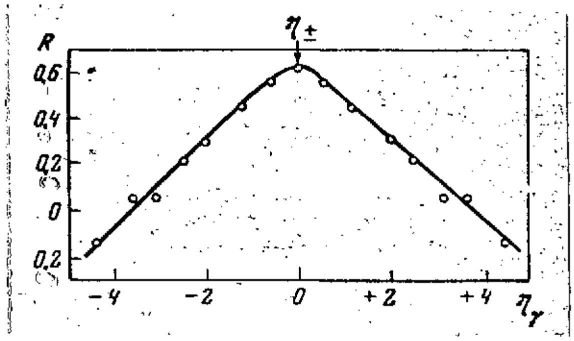


Figure 47. Angular correlation between emitted charged particles and γ-quanta in the interaction of colliding proton beams at energy of 15 GeV. On the vertical axis, the correlation coefficient R is plotted, with rapidity on the horizontal

*The concept of "short" or "long range" correlations are determined by the maximum spacing on the scale of rapidity for which the correlation coefficient is not equal to zero, and, consequently, the emission of one particle still influences the emission of the other.

Why Are Heavy Fireballs Necessary?

In order to judge to what degree the claim that one or another model is justified in explaining or only approximately describing the phenomenon of multiple particle production, not only is detailed information concerning the phenomenon in several energy regions important, but also the possibility of including a sufficiently wide range of energies. If the first condition can be satisfied only by means of experiments on accelerators, then in pursuit of ever higher energies, it is necessary to "hunt" for cosmic rays.

No less important is the choice of the detection method. In the case in which the energy of the initial particle exceeds 10^{12} eV, it is necessary above all to consider a detector with high spatial resolution, since the emission angles of the fastest secondary particles are calculated in thousandths of radians, or in units of minutes of arc.

Therefore, it is not surprising that photoemulsion technology with its unique resolution invariably attracts the attention of the cosmic ray physicist who is interested in particles of maximum energy, in spite of the fact that with increasing energy the particle flux swiftly decreases. But in this case the "fatal" question always arises: how is it verified that the energy is, in fact, high, and how are high energy events separated from the enormous number of background events of low energy interactions.

The simplest method of searching for and studying high energy ($\geq 10^{13}$ eV) events is to expose a multi-liter stack of emulsions at a high altitude, where the high energy primary /120
particle is not degraded by absorption in the Earth's atmosphere,

and to "rummage" at random through the whole volume of the stack in search of interesting events. In this case, an indirect estimate of the energy based on the angular distribution of the particles and the approximate conservation of transverse momentum is used.

In 1961, this very method led the author, M. I. Tret'yakov, and his colleagues to the observation of a very unusual interaction with the emission of 5 slow and 40 fast charged particles.

An analysis of the emission of the fast particles (which produced intermittent tracks in the emulsion) allowed one to obtain the following estimate of the total energy released:

$$E_0 = 1.5\bar{p}_\perp \sum \frac{1}{\sin\theta_j} \approx 1.5 \text{ [TeV]}$$

(1 TeV = 10^{12} eV).

The angular distribution of the particles is distinct from the majority of events in that the angles are confined to a small angular interval (3/4 of all particles lie in the interval 10' - 1°), and correspond to a practically isotropic distribution of at least 38 particles in their common c.m. system.

There arose the assumption that, in this case, an anomolously heavy fireball of mass no less than 20 GeV was formed, since for an isotropic distribution and a normal value of the average transverse momentum of each particle, an energy of about 0.5 GeV is necessary.

By means of a subsequent, detailed analysis of the structure of the angular distribution, the authors came to the conclusion that, in fact, four "normal" fireballs could have been formed. Their angular distributions, however, were distorted by the large transverse momenta received by each fireball as a whole. The idea of the cascade character was considered as a possible reason for the origin of such momenta: at first a heavy fireball could have arisen, which then decayed into several "normal" ones. These in turn decayed into separate pions. Incidentally, a similar hypothesis of formation and cascade decay of the fireballs is reminiscent of the Hagedorn school.

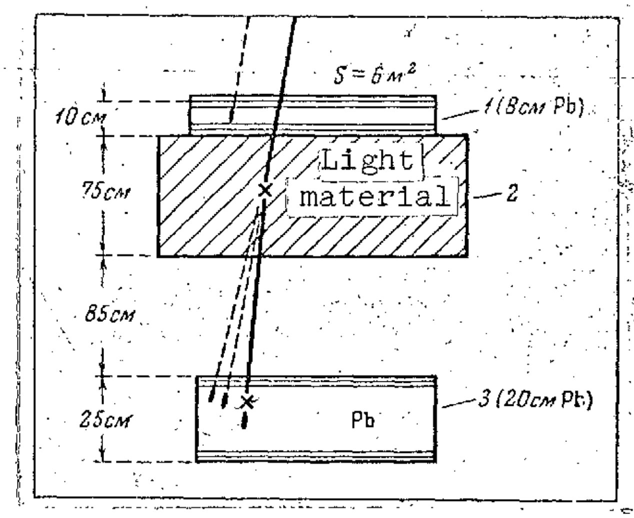


Figure 48. One of the variations of the large photoemulsion cameras for study of nuclear interactions at extremely high energies in the atmosphere:

1 — upper camera (detector of electrons e and photons γ which originate in the air); 2 — generator of secondary e and γ; 3 — lower camera (detector of secondary e and γ). The dashed line indicates a nuclear interaction; the solid line — the trajectory of the nuclear active particle; the dotted lines — the electrons and photons. The camera was set up on Mt. Chacaltaya (Bolivia) in 1965 - 1966 /121

Great significance obviously cannot be attached to a single case of observation of an isotropic angular distribution if no new observations are made pertaining to significantly higher energies. When physicists realized the impossibility of progressing further with normal photoemulsion stacks lifted for short times (30 - 40 hours) into the stratosphere, a new and widely general technique arose. The idea consisted of setting up photoemulsion chambers on high mountains. These devices have the form of an enormous "sandwich" of alternating layers of emulsions and lead; and the Earth's atmosphere is used as a target (Figure 48). In addition to nuclear emulsions, one also began to use "rugs" or thin and significantly cheaper x-ray film. In several similar experiments, long jet airplane flights at altitudes of 10 - 12 km were used.

In high mountain studies, a decrease in the altitude of the experimental apparatus is more than compensated for by an increase in area (up to 150 m^2) of the apparatus, and an increase in the duration of the experiment (up to a year). We note that through each square meter of area at the edge of the atmosphere, approximately 500 particles of energy 10^{14} eV and higher pass, and that only about 1% of these reach an altitude of 5 km. /122

By interleafing photoemulsions with lead, individual γ-quanta and high energy electrons originating in the air can be tracked, and by the development of the subsequent electron showers, their energies can be measured to sufficient accuracy (∿ 30%) if they exceed 0.2 - 0.3 TeV. This, in principle, opens up the possibility of studying the characteristics (emission angles and energies) of individual π°-mesons which originate in the process of multiple particle production on nuclei of the air. The advantage of an air target over solid matter is that for an appreciable divergence of the two γ-quanta, which originate from the decay of a π°-meson of energy ∿ 100 GeV in the air, a path length of no less than 100 m is needed. On the other hand, if the altitude of π°-meson creation exceeds 500 m, enough matter of the atmosphere itself is accumulated for the development of an electron-photon shower. Then, even the distribution of π°-mesons or even the "daughter" γ-quanta become extremely intricate.

N. L. Grigorov and colleagues (MSU) developed an apparatus for this. They placed a large ionization calorimeter under the photoemulsions. The colorimeter allowed one, first of all, to measure the energies of all charged pions incident on the device, and, separately, the energies of all the π°-meson decay products and, second, to signal the arrival of a jet of particles for the benefit of one or another section of the apparatus. Thus arose the so-called "controlled photoemulsion" method.

In experiments using the atmosphere as a target for processes of multiple particle production, Japanese physicists have achieved the greatest success, although they did not use the controlled photoemulsion method. Over the course of many years, they set up photoemulsion cameras of ever increasing area in Japan on Mt. Norikura (at an altitude of 2.8 km) and, then, in collaboration with a Brazilian group, on Mt. Chacaltaya in Bolivia at the world's highest (5.2 km) experimental station. The total power of all the operating cameras is characterized by their total "luminosity", i.e., the flux of cosmic rays during the entire period of measurement. The luminosity of each individual camera is expressed by the product of the total area (in m^2) of the photoemulsion layers in one stack by the length (in days) of the measurement time. The luminosity of the entire series of experiments is about 50 thousand. This is equivalent to a detector of hectare area 1, operating continuously for 5 days. /124

With such a luminosity one can count on observing the interaction of at least 1000 particles with energy > 10^{14} eV (100 TeV), of which about 10 have an energy greater than 10^{15} eV. Each interaction produces a large group (usually called a "family") of electron cascades of practically parallel rays in the counter. With proper skill, one can approximately recover the angular and energy distributions of almost all γ-quanta of energy greater than 1 TeV from the overall cascade distributions in the photoemulsion (Figure 49). These γ-quanta originate in the initial interaction of the incident particle with a nucleus in either the air at a

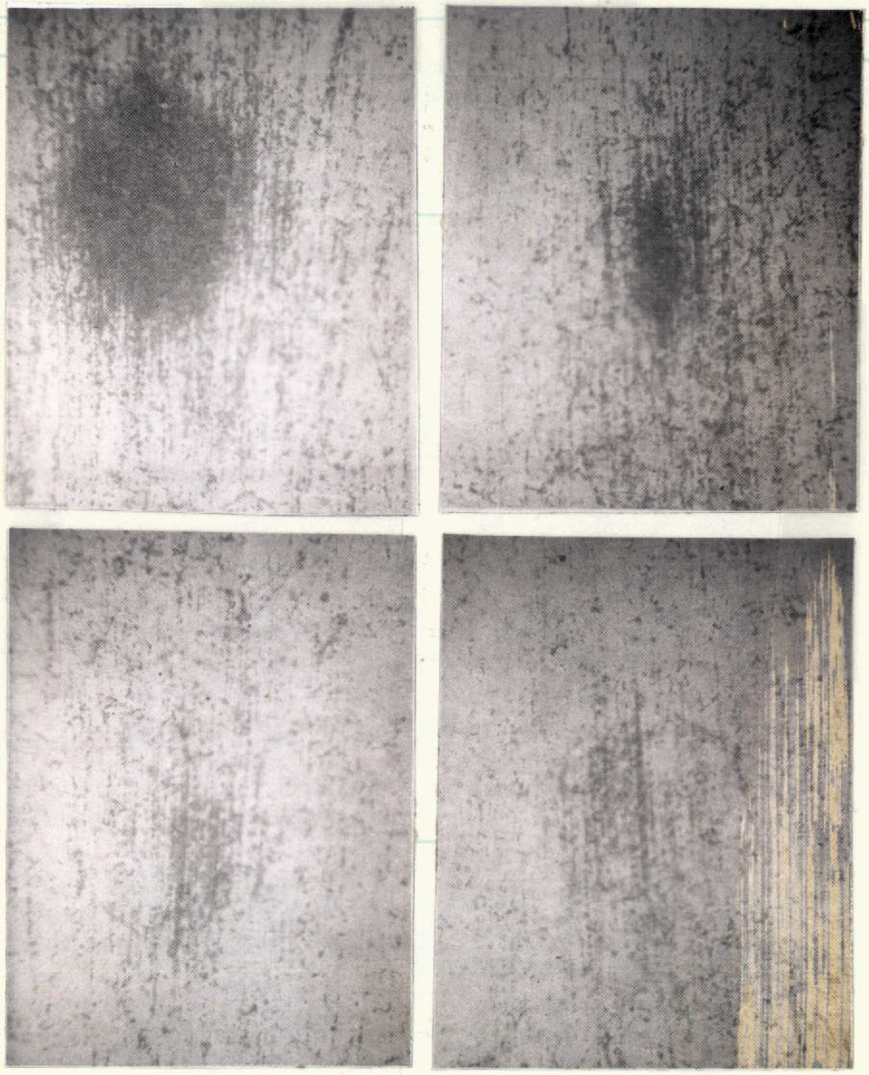


Figure 49. A family of cascade showers produced by a group of electrons and photons which arose from multiple π^0 and $\pi^{\pm}$ production in the atmosphere above the apparatus. Four fragments of the photoemulsion microphotograph are shown which represent the most powerful cascade family (data of FIAN, A. V. Ananasenko et al.)

height of several hundred meters above the apparatus, or in a special layer of dense material at a height of 1.5 m.

A careful analysis of many years of observations is usually made by the following method.

First of all, with the proper choice of Lorentz factor for the c.m. system, the angular distribution of the γ-quanta in that system (and from this, the angular distribution of the "parental" π°-mesons) is, as a rule, nearly isotropic. Subsequent analysis of the energy distribution, which must conform to Planck's formula, leads to the conclusion that the process proceeds via the formation of a fireball in the intermediate state.

But, if this is actually the case, then by means of a simple energy transformation (according to the theory of relativity), an important relation can be found between the total energy of all γ-quanta (ΣE_{γ}), the Lorentz factor γ_s, and the mass of the fireball $M_{f.b.}$:

$$3\sum E_{\gamma} = \gamma_s \cdot \mathfrak{M}_{f.b.}$$

The factor 3 on the left side of the equation is based on the assumption that π^{+} and π^{-}-mesons, which are not directly observed in the experiment, are emitted in equal numbers, and have the same energies as the detected (by means of their "descendants") π°-mesons. /126

All observed events are plotted on log-log graph paper (Figure 50), with the Lorentz factor γ_s on one axis and the total energy (ΣE_{γ}) of the corresponding family of γ-quanta on the other. A very curious picture is obtained. The majority of events are grouped within the limits of two bands, one of which (left) corresponds to "normal" fireballs of mass 2.5 - 6 GeV, and the second — to heavy fireballs of mass 15 - 30 GeV. The Japanese physicists called these fireballs heavy and super-heavy quanta. It is interesting that the masses of the heavy fireballs are close to the value obtained from the unique isotropic event observed by them in a photoemulsion in 1961.

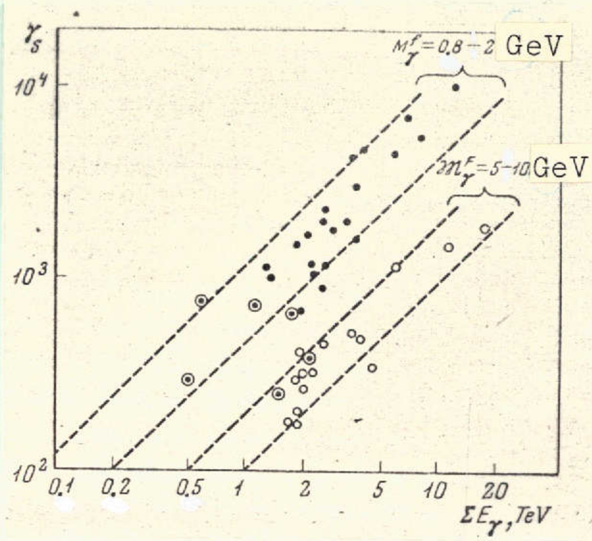


Figure 50. Distribution of groups of γ-quanta observed by the Bristol-Bombay group of physicists, and which lie in one of two basic classes: γ_s — Lorentz factor of the assumed fireball; ΣE_γ — total energy of all groups of γ-quanta; ⊙ — energetically distinct γ-quanta ("torpedos")

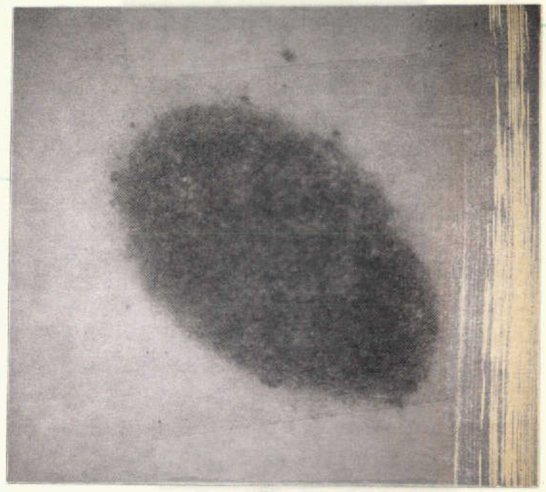


Figure 51. X-ray film record of a powerful cluster of electron cascades ("Andromeda"), to which is attributed an energy of about $4 \cdot 10^{14}$ eV. About 30 separate cascades, each of energy greater than 10^{12} eV were formed at the edge of the black spot in the photoemulsion

An even more massive fireball (or something similar to one) was observed on Mt. Chacaltaya in 1971. A photograph of this record-breaking event, which was given the exotic name "Andromeda" (evidently in analogy to the Andromeda nebula), is shown in Figure 51. A spot of high density with a radius of about 2 cm is evident in the photo. Within this spot one can distinguish with the aid of the nuclear emulsion ∿ 30 cascades of total energy ΣE_γ ∿ 400 TeV, and an additional 240 cascades of energy ΣE_γ = 550 TeV, which can be seen at the boundary of the spot. The total energy is even of a macroscopic value, since 10^{15} eV corresponds roughly to 1500 ergs, or about 1/30 of a gram-calorie.

The persons who observed the event consider that it originated in the atmosphere at an altitude of $\sim$ 600 m above the apparatus, and was produced by a particle of energy $\sim 10^{16}$ eV.

In conclusion, we will try to answer the question posed in the title of the chapter: do fireballs really exist?

In order to answer this question, it is necessary, first of all, to make clear what is understood by this term, which various scientists define differently. Most frequently, the term fireball means any sufficiently massive (not always identical mass, but not less than two nucleon masses), unstable cluster of strongly interacting matter which decays in a very short time (on the order of 10^{-24} sec) into individual free hadrons (principally charged and neutral pions).

Are such clusters actually formed in multiple particle pro- /127 duction? As we have seen, a sufficiently convincing, universally recognized answer has not yet been obtained by science. A whole series of experimental and theoretical data, examined in the previous chapter, leads to the notion that in very high energy hadron collisions, a cluster forms, expands, and then decays into particles according to the laws of thermodynamics or hydrodynamics, and that in the initial state there is nothing besides this cluster.

There are, however, other no less convincing experimental facts and theoretical considerations which support the contention that, in the initial stage of the process, there can be formed not only one, but several, clusters and, besides them, individual free particles or resonances. Such a broader and more "liberal" position seems to the author to be more valid. A discussion of the more concrete characteristics of these fireballs (mass, decay law, etc.) sometimes degenerates into a non-productive dispute over words ("fireball", "cluster", isobar, etc.) which attests to the lack of information concerning the essence of the matter.

CHAPTER 7. WHAT IS THE NUCLEON MADE OF?

A "Building Block" or a Detail of the "Architectural Design" of the Particles of Matter?

As far back as the beginning of the 20^{th} century, physicists /128
found it difficult to imagine things more incompatible than particles and waves, matter and radiation (almost like Pushkin's "genius and villainy"). Quantum physics of the twenties, which demonstrated the wave characteristics of particles, and the corpuscular nature of waves, shook this manner of thinking for the first time. In the thirties, the studies begun were continued. In cosmic ray experiments, the transformation of quanta of radiation into "very genuine" protons, electrons, and positrons was observed. Nevertheless, in this scene of events of the microcosm with its practically universal character of "reincarnation" of any particle of matter, there were strict prohibitions in effect which limited the scope of possible transformations. There are at least three of these prohibitions, which physicists usually express in terms of quantum numbers.

The first one (almost a commandment, if one speaks the language of spiritual particles) consists of the law of conservation of electric charge Z, thanks to which the photon "has the right" to transform exactly into a pair of particles with opposite signs of charge.

The second commandment is manifested by the following fact. Although nucleons (protons and neutrons) can be excited to a great variety of more massive particles and can easily be transformed into each other, the process of transformation of, say, a proton into a positron or a neutron into an electron-positron pair has not occurred with detectable probability (this has been demonstrated experimentally) over the course of existence of our Universe ($\sim$ 10 billion years). This prohibition is called the law of conservation of baryon number B, which is equal to +1 for protons and neutrons, and -1 for anti-protons and anti-neutrons. It is just for this reason that the conversion of a proton-antiproton pair into several π°-mesons, and after their decay, into "pure" readiation, namely γ-quanta, cannot be prohibited.

The third prohibition is expressed by means of the law of conservation of a peculiar quantity S with the unusual name "strangeness". It was found that in the process of multiple particle production, any number of neutral K-mesons (of mass about 500 MeV) can be created paired with neutral Λ-hyperons (of mass about 1115 MeV), but never only one of them, although it may seem that it is favorable energetically. The situation concerning the Ξ-hyperon (of mass about 1530 MeV) is even more complex. Its creation by means of nucleons requires the participation of already two K-mesons. Finally, in the production of the Ω-hyperon (of mass about 1675 MeV), a total of three partners besides the nucleon is necessary, as in the reaction $K^- + p \rightarrow \Omega^- + K^+ + K^0$. Everything is "in order" if one attributes to each of these hyperons a definite quantity called strangeness, which is numerically equal to -1 for the Λ, -2 for the Ξ, and -3 for the Ω. For the K-mesons, the strangeness is +1 (for K^+ and K^0), or -1 (for K^- or $\overline{K}^0$, the anti-particle of the K^0-meson). /129

Thus, the electric charge Z, baryon number B, and strangeness S are the three basic tenets on which the peculiar "jurisprudence" of the laws of particle transformation are based.

Occasionally, however, instead of strangeness, the combination $B + S = Y$ is used. This quantity is called "hypercharge". And instead of the algebraic (but always integer) quantity Z (in units of charge of the positron), the vector quantity T is used. Its projection T_z (on the z-axis) can assume both integer and half-integer values. The quantum number T is called the isospin.

The nine different combinations of the quantum numbers Z, B, S allow the representation of characteristics of not only the two nucleons and the five hyperons, but also the four resonances of identical mass 1236 MeV, which correspond to the four possible projections of the isospin T ($T_z = + 3/2, + 1/2, - 1/2, - 3/2$) for the baryonic Δ-resonances.

Therefore, it is not surprising that the idea occurred to the Japanese physicist Sakata, as far back as 1956, to "construct" all the particles known to him from combinations of three basic "building blocks" — the proton, neutron, and Λ-hyperon. The first of these provides the composite particle with its electrical charge, baryon number, and hypercharge; the second provides only baryon number and hypercharge; the third — only baryon number and strangeness. A value of zero for all these quantum numbers, including baryon number, can easily be obtained by combin- /130 ing the suitable particle with one of the three possible antiparticles. At first glance, it is difficult to get the required mass of the mesons, which, as a rule, are lighter than any three of the baryon "building blocks". But this difficulty is overcome if one recalls the mass defects of the atomic nuclei: the mass contributed to each by one nucleon is, on the average, almost 1% less than in the case of free nucleons. The numerical value of the mass defect in energy units is equal to the binding energy of the nucleon in the nucleus.

It is sufficient to assume that the binding energy is close to the rest energy of each free particle to immediately realize that the mass of the whole "construction" can become less than the mass of each "part" taken separately. It is true that, in this case, the idea suggests itself that the interaction of the "building blocks" must be extremely strong to correspond to the mass defect of the atomic number. However, this was not the reason for Sakata's failure. His scheme was unsuccessful because it was unable to explain the existence of the Ω^--hyperon (for which not even three Λ-hyperons suffice), which was discovered in 1964. But the initial idea, however, was resurrected in the same year by Gell-Mann, who proposed hypothetical particles called quarks as the elementary "building blocks".

The boldness and uniqueness of this hypothesis is emphasized by the fact that all quarks have fractional charge, not only electrical, but also hypercharge. Integer values are assigned only to the strangeness. The characteristics of the quarks are given in Table 2 (at first, there were three basic quantum numbers, and then two "derived" ones). /131

TABLE 2. HYPOTHETICAL CHARACTERISTICS OF QUARKS

Quantum number	Quarks		
	q_1	q_2	q_3
Electric charge Z	2/3	-1/3	-1/3
Baryon number B	1/3	1/3	1/3
Hypercharge Y	1/3	1/3	-2/3
Isospin T ($T_z = Z - Y/2$)	1/2	1/2	0
Strangeness S = Y - B	0	0	-1

By combining three quarks (not necessarily different ones), one can make any real existing baryon (a particle with B = + 1). A subsequent increase in the number of strange quarks (q_3) allows one to obtain all the hyperons up to the "strangest" hyperon Ω^- (for which Z = - 1, Y = - 2, and S = - 3, because $\Omega^- = q_3 + q_3 + q_3$).

In order to "build" the mesons, it is necessary to use pairwise combinations of quarks and anti-quarks (only then can one obtain zero baryon charge B = 0). The presence of one strange quark or anti-quark (q_3, $\bar{q}_3$) allows one to get the "strange" mesons, in particular, the K-mesons.

The use of quarks as "parts" for building hadrons makes possible the explanation of one of the general characteristics which is called the unitary symmetry of strong interactions. We will merely mention, without going into detail, that this characteristic can be regarded as a hypothesis concerning the composition of very strong interactions which are completely independent of all three fundamental quantum numbers, of the moderately strong interactions, which depend in a definite fashion only on the strangeness of the particle, and of the not very strong (but not weak) interactions, the electromagnetic, which depend on the electrical charge*. The combination of these forces of nature enables one to explain quantitatively the existence of special symmetry groups of particles called supermultiplets, whose masses

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*One of the graphic illustrations of the symmetry of strong interactions is the complete identity of the processes of elastic scattering of protons on protons and neutrons over such a wide range of momenta that the probability of scattering changes by a factor of a million.

are split relatively weakly due to the moderately strong interactions, and not at all by the electromagnetic. One finds, in particular, an explanation and a regularity in the increase in mass from the Δ-resonance to the Ω^--hyperon through the Σ- and Ξ-hyperons. Each time the increase is almost the same $\sim$ 145 MeV (it is sufficient to assume that there is the same quality between the mass of the strange quark and the two neutral ones).

In this manner, the quarks can be considered as universal "building blocks" from which any hadrons can be put together, both heavy (baryons) and medium (mesons). But, indeed, the baryons /132 are the basis of atomic nuclei, and this means the basis of matter in general. The mesons are the field quanta of the strong interaction, i.e., the quanta of the very radiation by means of which the baryons "communicate" with each other. Therefore, it can be considered that the quark hypothesis is directed at completely erasing any boundaries between matter and radiation.

The example of the quarks turned out to be "infectious" — based on their example, people attempted to confirm the existence of three other "foundations" for the light particles, the leptons. These attempts, however, are still in the preliminary stages of investigation.

The fundamental significance of the quark hypothesis was appreciated immediately by physicists (and not only by physicists). The "only" deficiency of this hypothesis is that nobody has ever been able to observe free quarks, but this fact has been and remains its advantage, since it allows the possibility of observing principally new phenomena of nature. The history of the positron is still well preserved in the memories of physicists. This particle was predicted by P. Dirac on a purely theoretical basis and served at first (until it was observed) as the main argument against his concept (even in the eyes of the author himself!), and after its discovery it provided the triumphal procession of theory.

One of the arguments used for the quark structure of hadrons is related to the additivity of the effective interaction cross sections of protons with protons and pions with protons. Since protons (like all baryons) are made up of three quarks, and a pion — of only two, one would expect that at an energy of 1 1/2 times greater (but equal from the point of view of one quark), the proton cross section would be 1 1/2 times greater than the pion cross section. This was confirmed by experiment: first, at sufficiently high energies, the ratio of the total cross sections was found to be 1.6 (38.5 mbarns for pp-interactions, and 23.7 mbarns for the average arithmetic cross section for π^+p- and π^-p-interactions) to within an accuracy of 3%; second, the individual reaction cross sections for the creation of a given number of pions in the case of πp- and pp-interactions changes with increasing energy in an analogous fashion, but with a "stretching" of the energy scale, also by a factor of 1.5 - 1.6 for incident protons compared to incident pions.

The quark model in its general form also explains the qualitative change of state of the created particles with increasing initial energy, in particular, the 5-fold increase in the relative number of anti-protons and π^--mesons for an energy change of about 20 GeV. This was observed by means of the colliding beam accelerator at CERN (at an energy $\sim$ 1000 GeV). /133

The fractional electric charge of the quarks and their consequent sharply diminished ionizing capability (at least for the quarks q_2 and q_3) can be considered as their principal distinguishing characteristics. The tracks of such particles in detectors should be easily distinguished from all others. It is not surprising that already for many years, physicists have been "sifting" with envious perseverance through millions of particles created in strong interactions at high energies on accelerators.

It became obvious very soon that if free quarks are produced, then only extremely rarely. As a result, exceptional precautions must be taken against all possible imitations. However, this did not perplex the physicists very much, who had experimentally discovered another, also relatively rare particle, the anti-proton.

An interesting maneuver to get around these background imitations was undertaken by L. G. Landsberg and his colleagues while working on the proton accelerator at Serpukhov. They made use of the fact that the formation of beams of secondary particles which are emitted from the internal target of the accelerator are determined by the magnetic deflection, the Lorentz force, which is proportional to the charge and the momentum of the particle. As a result, even very massive particles (with mass $\sim$ 3 GeV), which are created with no kinetic energy in the c.m. system of the colliding particles, will be transported by the channels of the experimental area in the same way as singly charged particles whose momenta exceed that of the primary particle by 70 GeV/C (a schematic diagram of the experiment is shown in Figure 52).

Still another experiment concerning this extremely important but complex problem was performed in 1972 on the colliding beam accelerator at CERN. During the course of the experiment, six million charged particles, created by collisions of $\sim$ 25 GeV protons, were passed through the apparatus. The lack of suitable quark "candidates" of charge 1/3 or 2/3 allowed one to place an upper limit on the cross section of quark formation at the level

$(3 - 6) \cdot 10^{-34}$ cm^2, i.e., roughly 100 million times smaller than the total cross section of two strongly interacting protons. Such a low estimate of the probability of "knocking out" quarks from nucleons is justified under the condition that their mass does not exceed 22 GeV (for charge 1/3), or 13 GeV (for charge 2/3).

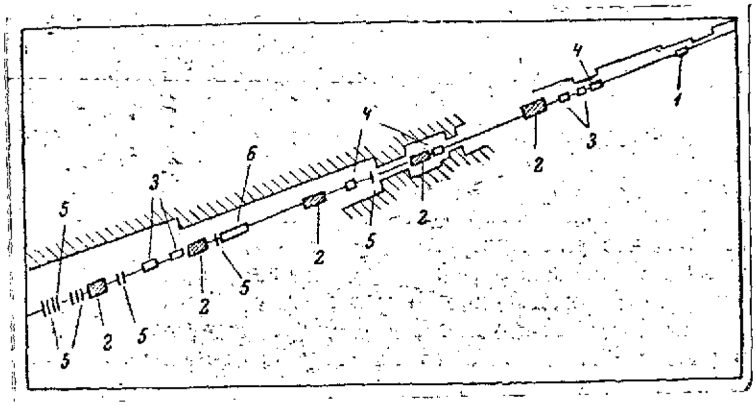

Figure 5.2. Schematic diagram of the experiment to search for quarks on the accelerator IFVE at Serpukhov: /134

1 — internal target of the accelerator; 2 — deflecting magnets; 3 — quadruple lenses; 4 — collimator; 5 — scintillation counters; 6 — Cerenkov (threshold) counter

The negative result obtained in these experiments, as in all previous ones, did not discourage physicists very much. In fact, the hypothesis of Gell-Mann does not predict the mass of the quarks. It allows an estimate of merely the order of magnitude of possible lower limits of this mass, which in fact is very high. Consequently, searches for processes of quark production at the maximum possible incident proton energies are included without hesitation in the research programs of all future accelerators.

It is natural that cosmic ray specialists have taken an active part in the resolution of such an important problem. As early as the end of the sixties, they were convinced that the possible fraction of quarks in the total flux of cosmic rays does not exceed one part in a million of one percent. But if the quark mass is high, very high energies on the order of 10^{12} eV or greater would be required for their "liberation". Therefore, the most serious attention has been directed toward the extensive atmospheric showers, the processes of creation in the atmosphere of a very large number of particles by the action of primary particles of energy 10^{14} eV, and higher.

In 1969, the Australian physicist S. MacCusker apparently detected several suitably low-ionizing tracks while recording the central particles of extensive showers in a cloud chamber. Judging from the calculations, however, these "phantoms" may well be the result of quite rare and very large fluctuations, deviations of the ionizing ability of the particles from the average value. /135

Therefore, new measurements are required which are significantly less sensitive to the ionizing ability of the particles in the extensive showers. In 1972, the West German physicist A. Bohm and his colleagues published the results which they obtained from 2120 hours of operating their apparatus, which included five series of proportional counters situated beneath a layer of lead 15 cm thick (to sift out electrons). This time, not one quark candidate in 107.5 thousand particle measurements was observed. From this, the conclusion was made that the flux of quarks from cosmic rays (if quarks exist at all) does not exceed one particle per one km^2 per second (per one steradian of solid angle).

At present, physicists are divided into two basic groups. One group, as in the past, sets its hopes on the experimental discovery of quarks, which they consider as the decisive confirmation of the entire theory of the unitary symmetry of strong interactions. The other group is inclined to consider it more probable that quarks do not exist at all in a free form, but rather represent the basic element of the mathematical abstraction which describes the symmetry characteristics of strongly interacting particles, and is something like a structural principle which constitutes the basis of the standard "architectural design" of these particles. One must not, however, exclude a third possibility which is related to the appearance of some kind of principally new concept.

The Unexpected "Breaking Open" of the Nucleon With the Help of Virtual Photons

We have already familiarized ourselves with the classical experiments of Hofstadter, who used the electron accelerator as a unique "high-power microscope" for "examining" the internal construction of the proton and neutron. In these experiments, the angular distribution of the elastically scattered electrons of /136
energy $\sim$ 1 GeV is studied, and the form factors are determined in the form of magnetic moment (for the proton and neutron) and electric charge (for the proton) densities which smoothly decrease from the center to the periphery.

Several years passed before significant progress was made in the construction of electron accelerators. Physicists were hoping for an increase in the resolving power of the device so that they could penetrate deeply into the "heart" of the nucleon. Striking progress on the way to this goal was made in 1968 by W. Panofsky and his colleagues at Stanford (U.S.A.) when a unique linear accelerator which produced a powerful beam of electrons of energy 20 GeV began operating.

In the first experiments using a special spectrometer and a hydrogen target, the number of electrons scattered at different angles was measured, as well as the electron energies. The high intensity of the electron beam allowed one to measure electrons scattered without energy loss out to an angle $\sim 15^{\circ}$, through which only one out of 10^{18} incident electrons is deflected. The cross section for this is on the order of 10^{-39} cm^2. The decrease in intensity of elastic scattering with angle is inversely proportional to the fourth power of the angle, as in previous experiments; and, consequently, it is inversely proportional to the fourth power of the momentum transferred to the nucleon.

But this was not the most interesting thing. Energy measurements showed that in several cases the electrons upon scattering lost a significant part of their energy, which could have gone into excitation of the nucleon to one of the already known resonance states. This was similar to what is actually observed in the scattering of atomic electrons of very low energy. In the given case, however, there appeared, together with the resonance peaks in the spectrum of electrons scattered with a significant probability, a non-resonant part which decreases continuously with energy, and which is related to the process of multiple production of some type of new, strongly interacting particle. And here in this non-resonant part, two surprising things were discovered.

The first is that the number of inelastic and non-resonantly scattered electrons decreases with angle much more slowly than the number of elastically scattered ones. /137

In order to quantitatively describe the degree of "spreading out" of any target particle, it is helpful to construct a form-factor curve, as in done in particular for "probing" proton structure by elastic scattering of electrons.

In Figure 53 the form-factors of the same target proton are given. They were obtained in two different experiments: one from elastic scattering (solid curve), and the other (experimental points) from non-resonant inelastic scattering with large energy loss. The almost horizontal form of the form-factor for the inelastic process signifies that the proton in this case assumes a "new form" as a point target.

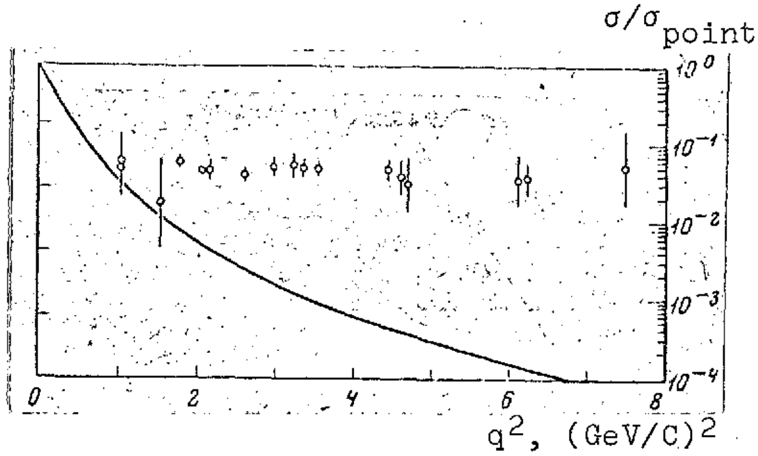

Figure 53. Comparison of the proton form-factor for elastic (solid curve) and inelastic (experimental points) electron scattering at incident energies of 3.5 - 19 GeV, and at angles from 6 to 26°. The square of the momentum transferred to the proton is plotted on the horizontal axis

First of all, one would expect that the structure factor W (the multiplier with which one multiplies the elastic scattering cross section at $\theta = 0°$ in order to obtain the non-resonant scattering cross section) will depend on two quantities: the energy loss ν of the electron, and the square of the 4-dimensional momentum (i.e., the mass) of the virtual photon q^2 (remember that the mass of virtual particles is not constant). In fact, the probability W, or rather the product of this factor and the energy loss ν was found to be a function of only one /138 variable ω, which is proportional to the ratio of the energy ν and the mass q^2. This unexpected characteristic (which appears only for sufficiently high energy losses ν) was given the name scale invariance or scaling.

In 1969, the American physicist R. Feynman proposed the following hypothesis for explaining the phenomenon of scaling. Let us assume that we will examine the structure of the target-nucleon, which is in a coordinate system moving at a speed less than that of light. One would expect that, as a result of effects predicted by the theory of relativity of time dilation and contraction of the longitudinal dimensions at such velocities, the structure observed will have a static — as if frozen — character, which includes some type of mutually independent "subparticles" which lack spatial extent (material points) but possess finite, but not very small effective mass. For sufficiently high energy transfers to this "subparticle", certain conditions can be met such that the interaction time of the photon with the subparticle can be significantly less than its lifetime. In such a case, the interaction process must have the character of an elastic scattering of the incident electron from one point-like subparticle. Such a point-like, free, and "almost" real subparticle in the form of a "building block", an instantaneous "construction" mold, was given the name parton.

It should be mentioned that the parton (like the quark) can have an effective mass significantly greater than that of an entire nucleon. If, however, in the case of "classical" quarks, it is implied that the "surplus" mass is almost entirely cancelled by the binding energy of the given quark to the others, then in the case of the parton, the emphasis is placed on its virtualness and short time of interaction. It is for this reason that the hope of detecting a free quark (at least one which has the lowest mass and must be quite stable) stubbornly continues, but talk of free particles outside the nucleus is evidently lacking in meaning*.

It subsequently became clear that Feynman's hypothesis is attractive because of its possibility of achieving an explanation, if only qualitative, of the anomolously high probability of the /139

*Until the idea of the parton, as well as the virtual hadron, contradicts experiment.

existence in nature of two inelastic processes which are related to multiple hadron production at a high expenditure of energy, but each time with the participation of leptons which are not directly capable of strong interactions. The first process can easily be represented by replacing the electron with a muon — a particle which in all respects (except for a significantly greater mass) is like a "second edition" of the electron in nature.

The second process is hadron production in high energy neutrino interactions with nuclei or nucleons. In this case, things are more complex: it turns out that the neutrino, like the electron or muon, can also undergo (if only rarely) scattering on nucleons, but in doing so, it is "simultaneously" transformed into either an electron or a muon, i.e., into its weak interaction "partners". In accordance with existing conceptions, the scattering of particles in weak interaction processes is very similar to scattering induced by electromagnetic forces. However, instead of virtual quanta of the electromagnetic field, the photons, virtual particles (quanta of the weak interaction), which are analogous to photons, are drawn into the picture. These virtual particles are called W-bosons, but have never been detected in a free state (possibly because they may have a record high mass, greater than 40 GeV).

These two processes, as well as the process considered in the beginning, called deeply inelastic electron scattering, have up to now not allowed one to detail the characteristics of particles.

It is important that partons "know how" to interact with virtual photons. This means that they must have an electric charge. To this is related the interest in the relative number of pions of different charge, which are produced in the process of deep inelastic scattering of electrons on protons. It was found that positively charged pions dominate negative ones. This means that the neutral virtual photon "knocks out" positively charged pions from the proton on the whole.

The parton model still commands the respect of many physicists because it increases the interest in the search for the "original mother" from which the enormously varied elementary (here in a limited sense of the word) particles originate. Heisenberg, whom we have already mentioned, was the last (but certainly not the first) to carry out such a search, but he was not able to carry it to a successful conclusion. His starting point was the quantitatively developed concept of the "original mother" described by the nonlinear differental equations which include a new fundamental concept. This concept contains the idea of an elementary length or "quantum of distance". In this conception, the "original mother" appears in the form of several universal fields which only in limiting cases of approximate description by linear equations can be quantized, i.e., be represented in the form of a sum of free particles or particles which almost do not interact with each other. /140

The partons can also be thought of as strongly concentrated clusters of several "original mothers" which occur in a state of continuous transformation, and which create such clusters according to the laws of probability in the form of very short-lived (but significant on the scale of energy) fluctuations.

Nuclear Cascades in Cosmic Rays and the Parton Model

A detailed study of the laws of the transformation of cosmic rays as they pass through the atmosphere has long been one of the main tasks of cosmic ray researchers. The investigation of the nuclear active (hadron) component of cosmic rays began 25 years ago, and even then, physicists tried to obtain information about their altitude and energy dependence. It turned out that the altitude dependence had an exponential character — the flux of particles with an energy greater than a given value decreases by a factor of e = 2.7 with an increase of roughly 120 g/cm^2 in the specific mass of air separating the experimenters from the boundary of the atmosphere. It was also found that, even if the quantity 120 g/cm^2, usually called the mean absorption length of the particle flux, depends on the effective energy threshold of the apparatus, then it does so only weakly.

In order to correctly interpret this constancy, it is necessary to examine to what degree another quantity is constant in nature. This quantity is the average range of interaction of hadrons with atomic nuclei of the atmosphere, and this range uniquely determines the transverse cross sections of nitrogen and oxygen nuclei. In connection with this, physicists for a long time have directed their attention to the fact that the particles of the highest energy (up to 10^{19} - 10^{20} eV) create powerful atomic showers, and these showers are maximally developed quite high above sea level. This means that even in a very wide energy range (almost 10 orders of magnitude), the average range of interaction of hadrons with nuclei of the air increases only insignificantly, by a factor of 1.5 - 2, if at all. /141

In order to quantitatively analyze all these regularities, it is necessary to set up and solve differential kinetic equations. These equations take into account the balance of the hadron flux of any given energy at any level in the atmosphere. The decrease in the flux is determined only by the interaction probability of hadrons with nuclei (in an infinitely thin layer), and the rise is determined, in addition, by the energy spectrum of secondary particles from all the high energy interactions.

An analysis of the kinetic equations shows that the independence of the range on the energy until absorption can occur if, in the process of multiple particle production, scale invariance (scaling) of the spectra of secondary particles is satisfied. This means that the form of the spectrum does not depend on the initial energy E_0, if one takes the corresponding energy E_0 as the unit of the energy scale for each interaction. Under this condition, the form of the energy spectrum of the hadron components as a whole is conserved at all levels of observation.

Experiment showed that to a first approximation, the independence of the spectrum of the hadron components of energy over quite wide ranges of altitude and energy is actually characteristic of cosmic rays (Figure 54). Here it is necessary to make one reservation. The sharp falling (almost as the inverse cube of the energy E^{-3}) of the hadron energy spectrum leads to the fact that, in the total balance of particles, secondary particles with energies not too different from that of the primary particle (the "leader") always play a decisive role. Therefore, even with the rigorous justification of direct confirmation (the invariance of the hadron energy spectra at all altitudes follows from scaling in the interactions), only a very approximate conclusion can be made concerning the justification of the inverse assertion: scaling in individual interactions follows from the invariance of the spectra with altitude. /142

It must unfortunately be stated that many (far from all, of course!) physicists who work on accelerators are not familiar with the achievements of cosmic ray physicists. They justify their lack of information on the basis of the approximate and sometimes contradictory character of the results obtained in this area. Apparently for this question arose the necessity of "rediscovering America" by starting from completely different considerations.

R. Feynman, the author of the parton model of nucleon structure, directed his attention to the fact that partons do not appear only in deep inelastic reactions involving electrons. If one considers colliding nucleons as a source of partons, then multiple hadron production can be represented as the result of mutual parton collisions (Figure 55. In order to make a quantitative prediction concerning multiple hadron production in such a model, Feynman had to introduce the more or less natural assumption concerning the spectrum of longitudinal momenta of the partons. He assumed that this spectrum is similar to the spectrum of photons emitted as braking radiation in collisions with atoms (more precisely, in the electric field of atomic nuclei). The spectrum of braking radiation has a quite simple form for the logarithmic scale of momenta. The number of photons emitted in a given momentum range is proportional to the width of this range: the range 1 MeV/c to 10 MeV/c, let us say, has as many particles as the range 10 MeV/c to 100 MeV/c.

For such a spectrum, the more numerous particles (or rather the ones having a greater probability of emission) are those with low energy (they are often called "soft", since low energy photons are absorbed very easily in matter). Starting with the braking radiation character of the parton spectrum and with the
additional assumption (also fully natural) of the low value of /144
their average transverse momenta, R. Feynman predicted the scale invariance of the particle spectrum which occurs in multiple hadron production by nucleons of various energies. Let us recall that the representation of the parton characteristics (like

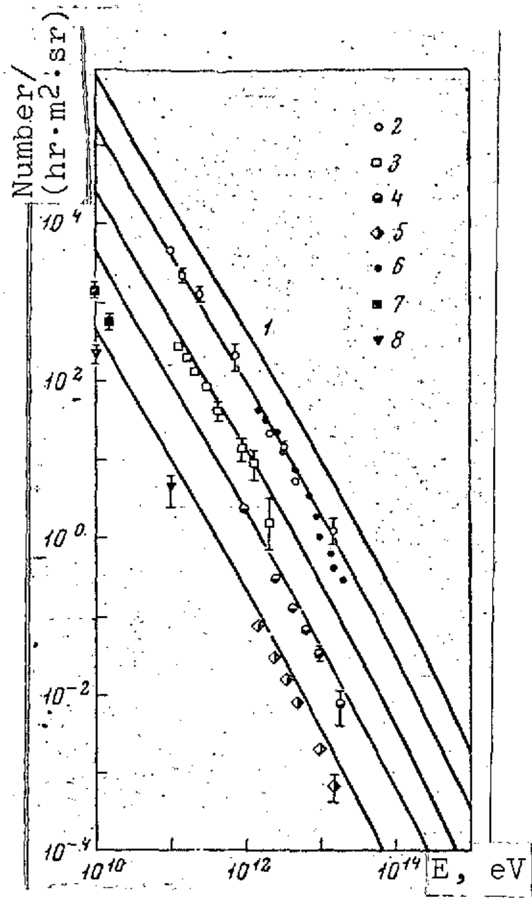

Figure 54. Experimental hadron spectra (protons and pions) of cosmic rays at various depths X of the atmosphere:

1 — primary radiation (X = 0); 2 - 5 — various ionization chamber data (X = 200 - 1000 g/cm^2); 6 — photoemulsion (X = 220 g/cm^2); 7 - 8 — magnetic spectrometer (X = 700 - 1000 g/cm^2). The smooth lines represent calculations based on the assumption of scale invariance of the multiple production spectra

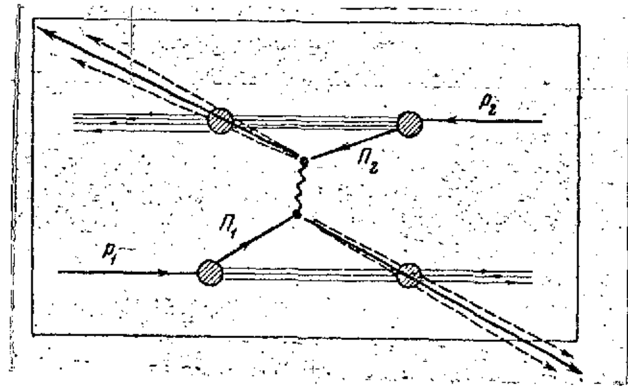

Figure 55. Schematic diagram of multiple pion production in pp-interactions by means of the interaction of partons (Π_1, Π_2) and the exchange of virtual particles

almost all free material points) is suitable only for the "observer" (including also the second parton) who moves at a very high velocity. This also means that the scaling hypothesis must be true only in the limit of infinitely high energies of the colliding particles.

It remains to be explained just which energies can be considered "infinitely high" from this point of view. Only a detailed experiment can answer this question.

The simplest way of doing an experiment is to measure the angular distribution of created particles. Actually, if one "piously" believes in the law of invariance of the average transverse momentum, then the distribution of longitudinal momenta characteristic of scaling will correspond to a just-as-characteristic "table-like" distribution of particle emission angles if it is expressed on a logarithmic scale of the variable $\eta = \log(\tan \theta_c/2)$, for which all angles θ_c refer to the c.m. system of the colliding nucleons. As previously mentioned, the data which has been obtained at CERN from the colliding proton beams at an energy of 30 GeV confirms the theoretical predictions (see Figure 46). An almost "table-like" (with sloping sides) angular distribution of the created particles was obtained. The width of the "table" is proportional to the logarithm of the energy of the colliding particles, and its height tends to a constant limit.

Good agreement with the predictions of the parton model was also obtained in measurements of the momentum spectra. At first it was compared with photons produced by intermediate π^0-mesons, and then with charged pions (see Figure 40). It is immediately obvious that the distribution of the ratio of longitudinal momenta $(X = p_{\parallel}/\bar{p}_{max})$ for a fixed value of the transverse momentum $p_{\perp}$ is practically independent of the initial energy E_0 from $E_0 = 500$ GeV and higher.

The following question may arise: how can one and the same set of data, which are plotted in Figure 40, explain both the fireball of Hagedorn and the parton of Feynman with equal success? It would seem that these two models have nothing in common. They in fact have general characteristics, not to mention the extensive possibilities of "fitting" each of these models to the data. If one first looks carefully at the parton scheme of multiple production (Figure 55), and then at the fireball scheme for the /145 same phenomenon (Figure 41b), then one can consider the first as some kind of definition of the second. Indeed, the parton model reduces high energy nucleon collisions to collisions between their constituent partons. But, if, as a result of the collision, both partons are torn out of the corresponding nucleons, then, because of their instability, they immediately become centers of free hadron emission, exactly as the fireball which was proposed earlier. Simultaneous with the "tearing out" of a parton from a nucleon, the nucleon can be left in a strongly excited, unstable state which is completely similar to the phenomenon considered earlier of the formation and decay of an isobar.

Particular interest has been recently devoted to the study of transverse momentum distributions $|p_\perp|$ of the created particles, expecially for the region of emission angles near 90°, when the longitudinal momentum $p_\parallel \doteq 0|$. Earlier, it was considered that the number of particles must very quickly decrease with increasing $|p_\perp|$, roughly as an exponential function of the square of the transverse momentum. The parton model, however, predicts that for sufficiently large values of $p_\perp|$ the effect of exchange between the two colliding partons by means of virtual photons must necessarily be expressed. This leads to a change in the distribution to a more gently curved form (roughly like $|p_\perp^{-8}|$).

A specific experiment to confirm this phenomenon using colliding beams led to a new, unexpected effect. It was found that the transition from the experimental curve to the gentle one occurred quite a bit earlier than expected (already for $|p_\perp \approx|$ 1.5 GeV/c), and the entire gentle portion was nearly 10,000 times higher than the calculated curve. This "surprise" was naturally explained by claiming that the partons can exchange not only photons, but also other virtual particles, including strongly /146
interacting ones for which the emission probability should be higher by a factor of approximately $(137)^2$.

At the same time, it became clear that among the created particles with anomolously large transverse momenta ($p_{\perp} \gg 1.5$ GeV/c), the fraction of heavy particles (K-mesons and protons) is also anomolously large; it approaches 50%. This may be related to the fact that the structure of the separately interacting parton is qualitatively distinct from the structure of the nucleon as a whole. Only in this case, the process, which is related to the "knocking out" of a single parton and its subsequent decay into free, stable particles, leads to a qualitatively different composition of created particles in comparison to the peripheral interaction of nucleons. It is necessary to remember, however, that the process of the deep inelastic type, which is related to the peculiarities of the partons as momentary point-like elements of nucleon structure, begins to play a significant role only at very high energies of the incident particle.

All the results considered in this section inspire the hope of entering the "Promised Land" of energies so high that with any further approach to infinite energy, no more qualitatively new natural phenomena will appear. This energy region is called the asymptotic region, or simply "asymptopia" in the polymathematical jargon of physicists.

On the other hand, the indications of a superheavy fireball and other phenomena, which cosmic ray physics detects at energies of $\sim 10^{14}$ eV and higher, permit one to think that maybe the idea of point-like subparticles (partons) is also limited, and sooner or later, the structure of even these particles will be discovered.

CONCLUSION: CONCERNING ADDITIONAL PROBLEMS AND NEW PERSPECTIVES

Paradoxes Within the Nucleons

Up to this point, the discussion has been concerned exclusively with multiple particle production in inelastic interactions of two elementary particles. In nature, however, the process mainly occurs with the participation of complex nuclei, as in the interactions of superhot and superdense stars (of the type of an exploding supernova), as well as with intergalactic matter. Together with the specific nuclear targets, it is necessary to take into account the nuclear composition of detectors of the photoemulsion type, and the propane or freon spark chamber types, as well as radiation shielding. /147

The study of processes involving nuclei, however, is important not only for their practical or methodological aspects. As will be shown below, the very process of multiple particle production changes very substantially, and occasionally even enigmatically, in the transition from elementary particles to nuclei.

We will take a complex nucleus as a target for strongly interacting particles, and we will think of it as a bag of closely packed apples. Actually, if the square root of the interaction cross section of protons with various nuclei is plotted as a function of the linear dimensions (radii) of these nuclei, then the resulting points (except for hydrogen) quite convincingly lie on a straight line which (with a suitable choice of scale) passes at an angle of 45° through the origin.

This can easily be understood if one considers that the external layer of the "apples" in the nuclear "bag" shields or hides the "apples" inside the layer; as a result, the total effective cross section is not proportional to the volume, but to the geometrical transverse cross section.

In the case of pions incident on the nucleus, the picture is different: the cross section increases with increasing mass number A (i.e., the number of nucleons in the nucleus), no longer in proportion to $\sqrt{A^3}$, but rather as $\sqrt[3]{A^4}$ (or $A^{3/4}$). Here, the appropriate analogy is not the "bag" of apples, but a package of half-transparent Christmas ornaments. /148

The presence of fully or even partially screened nucleons of complex nuclei leads to the idea of considering the entire process of multiple particle production on the nucleus as a result of successive (cascade) interactions within the nucleus with the participation of the second and succeeding "generations". At first glance, such a representation agrees at least qualitatively with the factor of appreciable increase in multiplicity — the number of fast particles produced. Table 3 presents data which show how, at incident energies of 8 - 20 GeV, the average number of fast charged particles produced by pions or protons changes with the replacement of the nucleon target by the heavy silver (Ag) or bromine (Br) nuclei. The choice of heavy targets is based on photoemulsion data so that the total number of slow protons, which are emitted by the nucleus as a result of direct recoil

TABLE 3. INCREASE IN NUMBER OF ($\bar{N}_s$) FAST CHARGED PARTICLES PRODUCED IN PION-NUCLEON COLLISIONS IN COMPLEX NUCLEI (RELATIVE TO A NUCLEON TARGET)*

Primary particle	Initial energy, GeV	Events selected acc. to "gray" (N_g) & black (N_b) tracks	$\langle \bar{N}_s \rangle_A$	Nucleon target, N_{so}	$\left\langle \frac{(\bar{N}_s)_A}{\bar{N}_{so}} \right\rangle$
π	17	$N_g + N_b \geqslant 8$	6,2±0,4	3,8	1,60±0,15
p	9	$N_g + N_b \geqslant 8$	5,5±0,3	2,6	2,10±0,15
p	20	$N_g = 3 \div 5$	6,4±0,4	4,0	1,6±0,1
p	20	$N_g \geqslant 10$	9,1±0,5	4,0	2,3±0,15
p	200	Nucl. W	16,7±3,8	7,65±0,17	2,2±0,6
$p, n(\pi)$	1300	Any N_g, N_b	18±3	11±2	1,65±0,4

*Commas represent decimal points.

("gray" tracks) or "evaporation" from excited nuclei** ("black" tracks) is not less than 8. Not simply any collisions with the /149 Ag or Br nuclei are selected for this, but rather basically "head-on" collisions which give 4 - 5 nucleons from the nucleus along the path of the incoming particle. A quite strong effect of multiplicity increase relative to two colliding protons occurs if the choice is made from the number of "gray" tracks N_g (proton recoils) without paying any attention to the number of "black" (N_b) tracks.

**The concept of nuclear evaporation is based on the far-reaching analogy between the nucleus and a drop of liquid. For strong (though local) heating of the nucleus, its individual particles obtain an energy which is sufficient to overcome the binding force with other particles and escape beyond the boundary of the nucleus.

In the quantitative analysis of the results, which are given in Table 3 along with many other results, a number of strange circumstances were found whose role increases in importance with increasing initial energy. The main one is that the effect of the internal nuclear cascade is small (it contributes only a factor of 1.5 - 2 to the increase in multiplicity, in spite of 3 - 4 successive cascades), and does not tend to increase even for a large increase of the initial energy. This leaves the impression that, in the process of internal nuclear cascades, only one very high energy (leading particle), as a rule, is capable of producing more particles.

An interesting attempt to study multiple particle production on very heavy nuclei was begun not long ago by a group of seven American physicists (J. Lord and colleagues). Using 200 GeV protons from the accelerator at Batavia, they irradiated specially prepared photoemulsions, which contained finely divided tungsten powder whose individual grains (granules) have an average diameter of 10 - 15 microns. The relatively small interaction probability of the incident protons with the tungsten nuclei (in 181 interactions in the photoemulsion in the first experiment, at most 8 interactions were observed within the tungsten grains) did not prevent the authors from establishing a series of important characteristics of the phenomena studied.

It was found that, on the average, 3.5 fast charged particles, which are emitted from a proton target at angles less than 90° in the c.m. system of the two colliding nucleons (in the forward cone), maintain their angular distribution practically unaltered in the case of a tungsten target. With increasing angle of emission, the contribution of particles also increases. This is conditioned by the presence of the heavy nucleus. With this, the comparison of processes, which occur on heavy and light

nuclei of the photoemulsion itself, led to the conclusion that the total number of surplus fast particles is proportional to /150
$\sqrt[3]{A}$ (A is the number of nucleons in the nucleus). The average number of slow particles (N_h), which are distinguished by their high density tracks, strongly increased. Relative to the average nuclear photoemulsion, this number increased by approximately a factor of 4, reaching almost 30 particles in each interaction. If one considers all the slow particles, which are recoiling protons from the tungsten nucleus, and compares their number with the total number of protons in the initial nucleus (74), then one must conclude that in the process of multiple production, no less than 40% of all the nucleons of the tungsten nucleus take part.

The authors themselves were inclined to explain their data by the occurrence of an internal nuclear cascade, for which each of the secondary particles, which appear in the collision of the incident nucleon with the first nucleon encountered in the nucleus, then undergo second, third, etc., interactions in the same nucleus.

This explanation, however, can scarcely be in agreement with the surprising invariability of the angular distribution of the fast particles which are emitted near the edges of the forward cone, and which carry off a principal part of the total energy of the initial proton. In order to resolve this puzzle, it is necessary to not only develop some type of new theoretical model of the phenomenon, but also to determine the extent to which the momenta of the particles in the forward cone are conserved in passing through the nucleus.

In order to clear up these paradoxes, several hypothetical considerations are attractive.

Hypothesis 1. As was noted by G. T. Zatsepinii, and then by E. L. Feinberg and other physicists, the interaction of the incoming nucleon with the first of the nucleons of the nucleus must lead to a partial tearing off of its dense meson cover ("coat"), which is responsible for the peripheral character of the majority of processes of multiple particle production. Since the restoration of the normal "coat" to this "half-dressed" (or "half-nude") nucleon requires a finite time, compared to its passage time through the whole nucleus, fewer additional particles are produced in subsequent collisions.

Hypothesis 2. Because of the contraction of the longitudinal dimensions of all rapidly moving bodies, the complex nucleus no longer appears to be a bag of apples from the point of view of the incoming particle, but rather a pile of "pancakes". Since the spreading of the strong interaction effect is finite, the /151 incident particle has time to interact practically instantaneously with the whole pile, or more precisely, with the "column" of "pancake dough" which it intersects. This effect ought to be particularly strong at energies exceeding 100 GeV, in which case it leads as if to a "drilling" of a tunnel in the "pile of pancakes". This explains why the excitation of the nucleus as a whole is relatively small. A quantitative calculation of multiple particle production can be carried out in the framework of the hydrodynamic model; this calculation shows that the average multiplicity ought to increase by only a very small power of the number of nucleons in the nucleus ($\sim A^{0.2}$).

Hypothesis 3. If one starts with the fireball model, then one can foresee that the increase with energy of the lifetime of the fast fireball, which appeared in the interaction with the "external" nucleon, leads in the end to the ejection of the fireball as an undecayed entity. The number of fast particles in this case can change only at the expense of the interactions of the primary particle, which carries off the remainder of the energy. However, if several fireballs were formed, then the slower among them have time to decay in the nucleus, and this distorts the angular and energy distributions of the slow part of the spectrum of the created particles. According to the data of the Polish physicists, all these qualitative effects were actually observed; and this permitted them to make an estimate of the lifetime of the fireball.

It must be admitted, however, than only a more detailed study of the interactions of nuclei using the most powerful contemporary accelerators will allow the possibility of tipping the scales in the use of one or another hypothesis.

The entirely non-trivial characteristics of the process of particle production on nuclei is also obvious in studies of the energy spectrum of particles. From the point of view of the primitive "ball" nodel for the collision of two "packages of Christmas tree ornaments", none of the projectiles obtain an energy greater than that of any of the incident "balls" taken separately. It is true that there are processes which take place, let us say, with the expulsion of particles of lunar matter as a result of meteors striking the Moon when this limit is not obeyed. But a priori, it is by no means clear to what extent cumulative processes, i.e., processes involving a concentration of energy in a small number of particles which are peculiar to /152
elementary particles, especially if one considers that the interactions of macroscopic bodies are related not to the strong, but to the electromagnetic interactions of particles. Therefore, the analogy with the meteor does not prove anything.

In 1971, the Soviet physicist A. M. Baldwin proposed that the processes of the cumulative type must also occur in multiple hadron production. The basic conditions of such an effect must be the chance encounter of at least three high energy particles in a volume whose size does not exceed the radius of the strong interaction.

A direct confirmation of this bold hypothesis was obtained from the results of an experiment which was recently performed on the large proton synchrotron at Dubna by V. S. Stavinskiy and his colleagues. The experiment consisted of studying the energy spectrum of the pions produced by deuterium (the nucleus of heavy hydrogen) which has been accelerated to an energy E_0 = 9 GeV. It was found that there was a significant "tail" of particles of energies greater than 4.5 GeV in the pion spectrum (Figure 56). Calculations showed that the probability of such an intra-nuclear accumulation of effects can be determined by starting with the probability of approach of three nucleons (two incident and one stationary) to within a distance not less than the strong interaction radius.

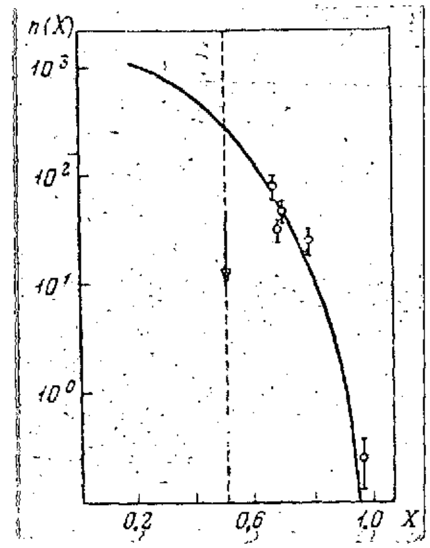

Figure 56. Experimental data of the spectrum of π^--meson production by deuterium in the region (X > 0.5) where the momentum of the pion exceeds the momenta of each of the deuteron nucleons and the spectrum calculated on the basis of the cumulative model (solid curve). The arrow corresponds to an energy of 4.5 GeV

Aren't There Too Many Models?

During the course of the entire book, the reader has had the opportunity to familiarize himself with both the basic, experimentally studied properties and the characteristic features of the process of multiple particle production and the models developed for the theoretical description and explanation of these properties in order to understand the essence of the phenomena, which confronted physicists as an enormous diversity of different reactions involving one, tens, and sometime hundreds of elementary particles. /153

A short summary of the basic experimental data is given by the following seven statements (if we limit ourselves only to hadron collisions).

1. The total proton interaction cross section σ_t (including both elastic and inelastic processes) almost becomes constant as the energy E_0 increases (usually to the region $E_0 \sim 50 - 70$ GeV). For energies greater than 100 GeV, the proton-proton interaction cross section begins to increase.

2. The average multiplicity of the process ($\bar{N}$) increases roughly as $E_0^{1/3}$ with increasing energy up to 50 - 70 GeV, and, subsequently, it tends toward a logarithmic law of increase. The topological or partial cross sections (for fixed multiplicity) pass through a maximum after a sharp increase at low energies (2 - 10 GeV).

3. The angular distributions N (θ_c) in the c.m. system of the colliding particles slowly become anisotropic, on the average,

as the energy increases (they are stretched out in the directions 0° and 180°).

4. The distributions $F_1(p_\perp)$ of transverse momenta pass through a maximum at $p_\perp \sim m_\pi c$ (m_π is the pion mass, c is the speed of light); the quantities $p_\perp^2$ decrease from the very beginning approximately by the same (exponential) law, which breaks down only for $p_\perp \simeq 1.5$ GeV/c.

5. In the distributions of longitudinal momenta $(p_\parallel)$, the "leading" particles stand out, especially in the case of low multiplicities. These particles carry off a momentum equal to the initial momentum (p_{max}), and tend to preserve the quantum characteristics of the initial particle (the baryon number, charge, etc.). The distribution of the momentum ratio $X = p_\parallel / p_{max}$ at sufficiently high energies (for a fixed value $p_\perp$) tends asymptotically to its limiting form. /154

6. The composition of the created particles at not very high energies (tens of GeV) is distinguished by the pronounced dominance of pions with a significant admixture of K-mesons, and a small number of anti-nucleons. At energies of hundreds or thousands of GeV, the fraction of K-mesons increases significantly and the anti-nucleons — very strongly.

7. For energies $\geq$ 10 GeV and for sufficiently high multiplicities, there is a tendency in the initial stage of the interaction for the particles to unite into more massive blobs ("clusters", or fireballs).

At least eight theoretical models, the classification of which is given in Table 4*, are invoked to quantitatively describe these seven fundamental facts. It is necessary to note that another series of models has been purposely excluded, since they are either poorly developed quantitatively or are of only historical interest, and do not withstand the "criterion of practice" (there are only a few in this category), or have a too restricted range of applicability, or, finally, yield to a physical interpretation only with difficulty and have a formal mathematical character.

The basic points for which the given model in the table agrees (or at least is not contradicted) with experiment are indicated by a plus sign.

At first glance at the table, one discerns the situation which is often summarized at scientific conferences in the form of the thesis: "almost all models describe almost all experimental facts"** (moreover, those who like categorical statements do not even use the qualifier "almost").

In connection with this, we would like to direct particular attention to the column of Table 4 in which are compared the different predictions of the dependence of the average multiplicity of the production of particles on the energy E_0 of the initial hadron. The prediction of the multiperipheral models is that a

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*From the point of view of the mechanism of multiple particle production, the last two models are merely variations of the same idea.

**The single minus sign in the table indicates not so much a direct contradiction of the hydrodynamic model by experiment as the biased interpretations of the corresponding experimental facts.

TABLE 4. THE BASIC MODELS OF MULTIPLE PARTICLE PRODUCTION

Model class	Model	Primary authors	$\sigma_t(E_0)$	Fundamental results (predictions of dependencies) $\bar{N}(E_0)$	$N(\theta)$	$F_1(p_\perp)$	$F_2(p_\parallel)$	Particle comp.	Fireballs (clusters)
Peripheral	Regge exchange	Ter-Martirosyan, 1963	+		+	+	+	+	
	Extreme fragmentation	Yaig, 1970		+					+
	Multispherical model	Chan-Loskevich-Allison, 1968		$\bar{N} \sim \lg E_0$	+	+	+		+
	Multi-fireball model	Dremin-Roizen-Chernavckiy, 1969	(+)*	$\bar{N} \sim \lg E_0$	+	+	+		+
Statistical	Thermodynamic	Fermi, 1950 Pomeranchuk, 1951		$\bar{N} \sim E_0^{1/4}$	+	+		+	+
	Thermodynamic (+ addl. assumptions)	Hagedorn, 1965			+	+	+	(+)*	(+)*
	Hydrodynamic	Landau, 1953		$\bar{N} \sim E_0^{1/4}$	+	+	+	+	−
Structural	a) Quark model	Gell-Mann, 1964						+	
	b) Parton model	Feynman, 1969			+	+	+		

*These results are postulated, not deduced.

dependence of the type $\bar{N} \sim \log E_0$ must result when the longitudinal momenta of the particles in the c.m. system begin to substantially (by several times) exceed the transverse momenta. And, in fact, at energies $E_0 \geq 50$ GeV, the experimental data for the average number of charged particles fits the simple formula: /156

$$\bar{N}_s \simeq 3.5 \lg E_0 \text{ (GeV)}.$$

fairly well.

However, the proponents of the hydrodynamic or thermodynamic models point out that their predictions for energies accessible to contemporary accelerators also agree fairly well with experiments. Several authors even propose generalizations of the formula which determines the average multiplicity for arbitrary energies and which, for sufficiently high E_0, is given by the particularly simple form:

$$\bar{N}_s \simeq 2E_0^{1/4} \text{ (GeV)}.$$

That is why the high energy "gap", which physicists are trying to reach by using cosmic rays, is so important. They maintain that the logarithmic law clearly gives a decrease in the multiplicity for energies on the order of 10^{14} eV and higher (energies which determine the development of extensive atmospheric showers).

No less important is the analysis of the distributions of the multiplicity about the mean value. As was noted in Chapter 5, in the hydrodynamic model, it is difficult to explain the experimentally observed wide distribution (for which the average spread exceeds the average by a factor of 2), and a rigorous quantitative analysis of this distribution has not yet been made. There

is great interest in this regard in the analysis of pair correlations between the angles of emission of the particles. This has been carried out for a series of colliding beam experiments on accelerators. The observation of obviously expressed correlations in conjunction with the "anomolously" large spread in the multiplicity of the created particles leads many specialists to the conclusion that at least two different types of hadron interactions exist. One of these possibly fits into the framework of the multiperipheral model, and the other apparently is somehow related to the process of diffractive production of particles. /157
It is true that an investigation of the characteristics of this second process at energies on the order of 10^{12} eV has not succeeded as it should.

Does this abundance of more or less "suitable" models signify a multivaluedness of truth, a concession to a philosophical relativity? Or is this perhaps an exceptional temporary situation during which scientists are trying different approaches to one and the same process, methods of stressing its different aspects, approaches which in the future will fuse into a single, rigorous theory in analogy to the way in which quantum physics realized a limited synthesis of the wave and corpuscular descriptions of matter? Or, finally, will there occur in the future a "revaluation of values" when some initial ideas are found to be senseless, similar to the cases of phlegm in the science of heat phenomena or to ether in the electromagnetic theory?

To the author, it seems more probable that the majority, if not all, do not exclude one another, but rather complement each other. And, although there is a close internal relationship between the models, processes in nature of a quite different type can occur even for the same initial conditions of the collisions.

In order to substantiate this point of view, we will consider the interrelationships of the models first within the limits of one class, and then between classes.

The simple peripheral models of the single particle exchange type, which completely suffice, let us say, for the description of diffractive disassociation, can be thought of as a particular case of a more general multiperipheral model. The latter model allows one to understand how "clusterization", the union of the particles into one blob, similar to a fireball, occurs as multiplicity increases. As the research of the Soviet theoretician V. N. Gribov and his colleagues showed, such a model, in the case of sufficiently high energies, logically and unavoidably leads to the decay of the single blob into particles which are distinctly separate. One ends up with something like a gas which is in its critical state and which tends to condense into individual dense drops of matter. In order to find the degree to which the effect of "clustering" provides for the decay of the single blob into two (or more) fireballs, more detailed investigations of the correlations between the momenta of the particles at energies of many thousands of GeV and higher are needed. Experiment does not /158 yet let us understand this as we should. But, if such a possibility is lacking, then the multiperipheral model will be similar to the multi-fireball model in a known way.

We will move on to the statistical models, which completely disregard any internal structure of the colliding particles. The neglect of structure, as was noted in Chapter 5, can be justified either in those special processes such as particle annihilation, or for those particles (subsystems) of a more complex structure relative to the system. In the Hagedorn model, the attempt is made to break up the complex structured system into a large number structureless systems, which are subject to the laws of thermodynamics, and which participate in collective longitudinal motion.

The physical grounds of such collective motion on the basis of macroscopic analogies with the dynamics of non-equilibrium condensed liquid are given by the model of Landau and its validity by the fundamental success of the concrete definition of this analogy (in particular, by the correct choice of the equations of state of the liquid).

An additional substantiation of the legality of this macroscopic analogy was made with the help of quantum field theory. On the other hand, the structural specifics of the initial state (before the collision) for a large number of created particles are considered as immaterial in this model. It may be that it is necessary to "pay for" this shortcoming by the absence of concrete predictions concerning the nature of the leading particles.

The quark and parton models bring us back to the problem of the internal structure of hadrons in general and nucleons in particular. Quarks can be considered (until contradicted by experiment) as simply concrete variations of the more general parton model. At first glance, both of these structural versions are totally different from the structural models of the peripheral theories: if quarks and partons are like little seeds submerged in the "depths" of a type of raspberry jam, then something rather like a cherry with a dense core ("pit") and a loose covering figures in the exchange of virtual particles. In fact, these two crude analogies are by no means mutually exclusive. We have already convinced ourselves that in the example of the simplest process, elastic scattering, the form (or more precisely, the /159 form-factor) of the colliding particles gradually changes, depending on their relative velocity. In principle, one can imagine how quantitative changes in structure turn into qualitative ones at sufficiently high velocities. The quark and parton models only differ in nonessential details. The important thing is that they consider different aspects of internal structure: the parton model is concerned with the space-time character of the elementary particle structure, and the quark model considers those degrees of freedom which are reflected in the quantum numbers (charge, hypercharge, isospin) of the same structural elements. Therefore, quarks can also be considered as concrete manifestations of partons. Together they are preparing the way for the explanation of the phenomenon that the quarks exist only in a virtual form, and not as real particles. Experiment has not yet excluded the completely different possibility that partons will turn out to be the more or less usual (except for their virtuality) hadrons. However, from general considerations, one can consider that the transition to small scale structural elements will be accompanied by a large increase in their mass.

We will now consider the interrelationships between the different classes of models.

At the beginning of Chapter 5, we discussed the fact that a statistical factor in the form of the influence of the phase volume on the total probability of one or another reaction appears without exception in all peripheral processes right up to the diffractive disassociation of particles. In any peripheral model, one can make a more or less clear distinction between kinematics, which is determined only by the size of the available phase space volume (to the first order by the possibility of the distribution of momentum among a given set of particles), and dynamics. The latter is related to both the characteristics of the strong interaction between particles and the character of the initial and final states of the system (in the form of wave functions), including the selection rules which result from the conservation laws of various quantum numbers of the system.

The purely statistical models, which do not consider dynamics at all, can be considered only as limiting cases which occur only for complete "mixing" of all the created particles, and one /160
of the reasons for this mixing is the large number of particles, a number so large that in a first approximation the system of created particles can be considered as a continuous medium in equilibrium with the radiation.

However, there remains first the question of how (thermodynamically* or hydrodynamically) to regard the state of the field until it decays into individual quanta, the particles, and, second, to what degree and in what stage of the process are corpuscular considerations admissible.

We conventionally called the final class of models structural ones, in spite of the fact that in peripheral models the structure of the initial particle is considered in one way or another, in the case of the dynamics, related to virtual particle exchange. However, in the quark or parton model, one is concerned with a more or less higher order structure — the corresponding processes of deep inelastic scattering have been justly named (in the case of electromagnetic interactions); let us recall that not only baryons, but also mesons and resonances can be "constructed" from strongly bound, very heavy subparticles. It is sufficient to make the fully natural admission that not all the "subparticles" are equally bound to one another. Therefore, a sufficiently strong perturbation does not have time to spread to all the internal bonds (or degrees of freedom), and we will, consequently, conclude that at very high energies, "second order" structure can be determined. The appearance of this more or less deep-structure in a definite stage of the process (or decay into free particles) again requires a calculation of the statistical regularity.

In considering the parton model, a comparison of the nucleon with a tree suggests itself. Ripe fruit hangs on its branches, and with a relatively small, but sharp, jolt, individual fruits break away, and as a result of their high energy concentration, they immediately "burst" and decay into particles.

The Route Upwards on the Ladder of Energy

Things which are difficult to understand are encountered not only in physics. Thus, for example, the American anti-positivist philosopher N. Hanson gives, in the book Perception and Discovery, the following definition of the concept of a scientific fact: /161 "Facts are those aspects of the real world which can be represented in an isomorphous correspondence with the design of additional accessory proposals." At first glance, this highly abstruse formulation, which even smacks of idealism, emphasizes the close connection between the result of the scientific observation and its interpretation from the point of view of the current notions of the essence and causes of the corresponding natural phenomena.

For this very reason, the author in all the preceding chapters has tried to maintain a not too large distance between the statement of experimental data of multiple particle production and the description of "suitable" theoretical models of this complex phenomenon. But each model is indeed a hypothesis, and a hypothesis is not simply a "rough draft" of one among several possible theories, but rather a question posed by nature. The meaningfulness and value of each such question is characterized best by its predictive force. Therefore, the question itself is desirably formulated in the form of a logical consequence: if the facts A, B, etc., which we observed, are explained by such and such a model of the phenomenon, then from this, the new facts A_1, B_1, etc., must unavoidably follow (this means, one must verify that this is so).

Now it is already clear that the persuasiveness and value of each stated hypothesis is determined by the scope of the phenomena it includes, relative to the physics of strong interactions. That is why models which allow a description from the same point of view of both elastic and inelastic interactions of nucleons, pions, K-mesons, and other hadrons, processes of particle production in any reasonable numbers and of any type, and the variation of the initial energy over a very wide range are more appealing. Moreover, as we convinced ourselves in the example of the parton hypothesis, the analysis of phenomena in which strong interactions are combined with the electromagnetic, and perhaps with the weak, promises better prospects.

It is very important to discover the profound and intimate relationships which exist among the classification principles of the elementary particles (above all, the symmetry principles of the strong interactions) and the laws of their multiple production.

Great hopes are placed on the region of asymptotically high /162 energies, in which is expected, on the one hand, a simpler form of the law of multiple particle production and, on the other, an obliteration of the differences between particles and antiparticles and perhaps even between all hadrons in general.

The entire discussion of the arguments here allow one to justify and understand the impatience and enthusiasm which physicists (both experimental and theoretical) show with respect to the most rapid construction of accelerators, which are designed to produce higher and higher beams of unstable particles. This route upwards on the ladder of ever increasing particle energy is very, very difficult. It requires the continuous progress of particle accelerator technology, and the solution of an entire series of "accompanying" high class engineering problems. It is sufficient to mention such requirements like the huge radii of the orbits of the accelerated particles, which increase in the normal ring-shaped accelerators in proportion to the energy attained, the necessity of high vacuums in very large volumes (especially in colliding beam accelerators), the development of large electromagnets with superconducting windings (as with accelerators, so it is with detection apparatus), the development of electronic computers with enormous memories and high speed operating capabilities.

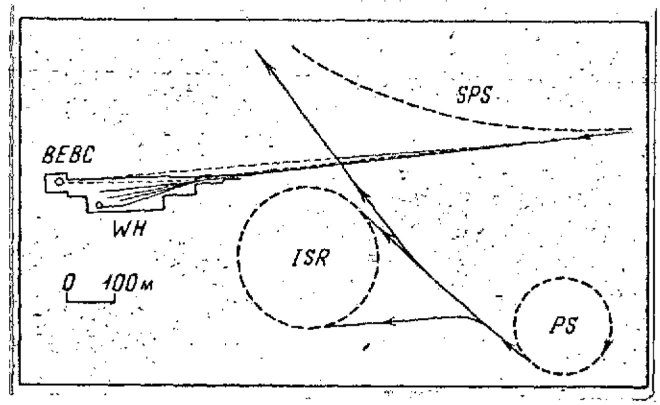

Figure 57. Layout (to scale) of two existing and one projected accelerator at CERN:

PS — proton synchrotron designed for energies up to 31.5 GeV; ISR — storage ring for intersecting beams; SPS — proton "supersynchrotron" for 300 - 500 GeV; BEBC — large European bubble chamber; WN — one of the experimental halls with the transported beam of particles

By way of illustration of the scales of contemporary installations, we have reproduced a scaled schematic drawing of two existing and one planned (for energies of 300 - 500 GeV) proton accelerators of the European Center of Nuclear Research (CERN) in Geneva (Figure 57).

Roughly the same energy (400 GeV) has already been reached by the American accelerator at Batavia, which has a diameter of approximately 2 km (Figure 58)*, where methods are being investigated to increase the proton energy to 1000 GeV. At Batavia,

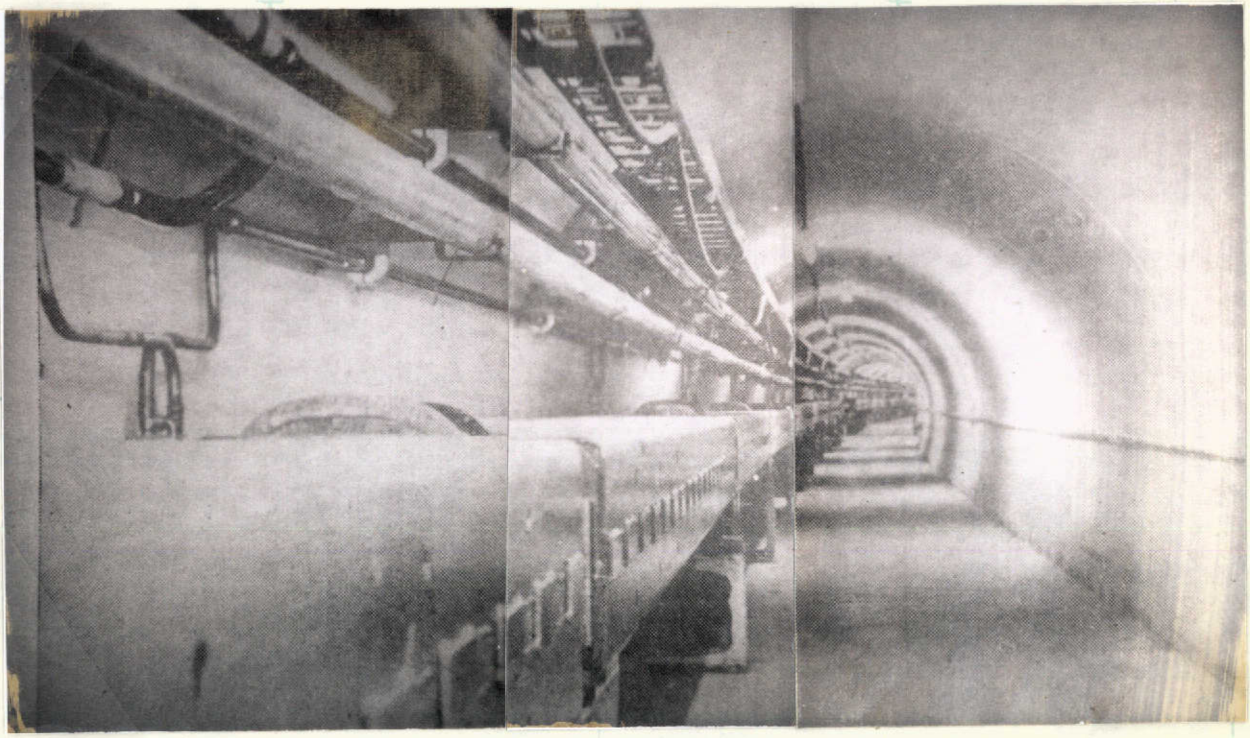

Figure 58. Part of the ring-shaped tunnel of the accelerator at Batavia (U.S.A.), in which, in December, 1972, protons were accelerated to an energy of 400 GeV. The diameter of the accelerator is about 2 km

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*The author wishes to make use of this chance to express his profound gratitude to the Scientific Information Service of CERN, which provided Figures 8, 10b, 45, and 58 of this book.

there is also a realistic project to construct storage rings and intersecting beams of particles of such an energy that would allow particle interactions at an effective energy of 10^{14} - 10^{15} eV by the beginning of the 80's. /163

By now physicists are beginning to get used to gigantic bubble chambers similar to the 2-meter hydrogen chamber "Mirabelle", which began operating at Serpukhov in 1972. Accumulated experience allows a further increase of the volume of detectors of both this type and the simple, more basic ones, like, for example, the use of a complex of spark chambers in a magnetic field (magnetic spectrometer), which allows one to measure particle momenta to within an accuracy of $\sim 1\%$.

The new "generation" of accelerators, the energies of which are reckoned in hundreds of GeV, have already begun to bear first "fruit". In particular, very important data concerning the distribution of the number of particles produced at these energies and the correlations between their emission angles have been obtained. In the very near future, there will be a decisive test of these models of multiple production which categorically predict the emergence of a logarithmic dependence of multiplicity on the initial energy.

In view of the forced and extremely expensive "megalomania", /165
physicists and engineers are intensely working on fundamentally new methods of accelerating particles. The idea proposed by the Soviet physicist V. I. Veksler of the collective acceleration of protons and nuclei was found to be very promising in this respect. It consists of accelerating not the heaviest particles, but rather rings of electron current with the ions interspersed among the electrons. The current rings are used in the capacity of stable blobs of plasma. The electrons, which are moving about

in this plasma, more or less "pull" the positively charged nuclear particles (in the form of ions) along with them. An experimental set-up which works by this principle has been recently built at Dubna by a collaboration of scientists and engineers under the leadership of V. P. Sarantsev, together with Veksler.

The continuous progress in accelerator technology does not leave the cosmic ray physicists indifferent either. An apparatus is being built at the present time in the Pamir mountains (at an altitude of about 5 km) whose area is of the order of 1000 m^2, on which several sets of x-ray film will be interleafed with lead filters. Such an apparatus allows one to study the families of photon quanta which are produced (by means of intermediate π^0-mesons) in processes of multiple particle production on nuclei in the atmosphere at energies of at least 10^{15} eV. The participants in the experiment are preparing to use hadron "blocks" — multi-layered "sandwiches" of lead and photoemulsions which permit the registration and measurement of the energies and emission angles of the penetrating particles (hadrons) created simultaneously with the π^0-mesons. In view of the very time-consuming nature and the fundamental significance of the work, a scientific collaboration of an entire series of laboratories in Moscow and the republics is taking part in this effort.

At the present time, it is difficult, even impossible, to foresee what will allow man to penetrate deeply into the fundamental laws of strong, electromagnetic, and weak interactions of particles. Currently, only general statements can be made concerning their features. Above all, this is wisdom, an understanding of how the "building blocks" of the surrounding world are constructed, and how they behave, not only under normal conditions on Earth, but also under completely different conditions of superhigh temperatures, which are also characteristic of other very hot "spots" of the contemporary Universe and of the superhot stages of development of the entire Universe in the remote past.

On this basis, the most varied possibilities of technical applications can appear, starting from the new sources of highly /166 concentrated energy, methods of storing it, transforming it, and transmitting it, and thereby realizing new methods of communication which know no obstacles or hindrances, perhaps on the scale of the remote cosmos.

The carping reader will remark here that the author is being carried away by groundless, unfounded fantasies and conjectures. To a significant extent, this is true. But if no conjectures are made, then there remains only to refer to the parable of Euclid. When one of his disciples tried persistently to find out what the practical applications of the studies of parallel lines were, Euclid called a slave and said approximately the following: "Give this young man some coins and let him go: he came to me not for knowledge, but for profit."

Twenty centuries separate us from the era of Euclid. The experience of the development of human civilization shows that the gap between "pure" knowledge and its practical use remains an advantage. It even becomes deeper and, at the same time, shortens. It deepens because in order to understand the even more profound, universal, and fundamental laws of nature, especially in physics, a very high degree of abstraction is necessary, and this operates by means of concepts and a mathematical apparatus which has only a remote relationship to that which can be directly observed, even in delicate laboratory experiments.

This gap shortens because the time lag in bringing the scientific achievements into production has decreased, the percentage of the population engaged in scientific activity has sharply increased, and experimental science rests on the very foremost technological achievements of the era.

In purely practical and even financial areas, the expenditures on the basic sciences are not so great. As S. F. Powell remarked in his Nobel Laureate address, "Everything which has been spent by mankind on this noble activity is repaid by two weeks production of world industry." And, at the same time, the whole economic structure and, in general, the entire appearance of contemporary civilization rest, in the final analysis, on the strong foundation of knowledge which in one way or another originates in pure curiosity.

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